

BENTHIC FORAMINIFERA OF THE WESTERN GULF OF MAINE 60 YEARS LATER: A PILOT STUDY COMPARING CHANGES IN SPECIES DISTRIBUTIONS

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ABSTRACT

The Merrimack River paleo-delta formed during the late Pleistocene as post-glacial rebound produced a local low stand in sea level. Subsequent sea-level rise drowned and eroded the paleo-delta, which is now reworked by a variety of processes. This study used benthic foraminifera as a biotic and environmental proxy to evaluate the sand and gravel resources of the paleo-delta.

Nineteen box-core sediment samples were collected from the paleo-delta along two east–west depth transects east of the Merrimack River mouth and off Plum Island, Massachusetts. From these samples, 62 species of benthic foraminifera were identified. When compared with distribution studies published over 60 years ago, some species have shifted landward in their distributions (e.g., *Adercotryma glomeratum*, *Cibicides lobatulus*, *Reophax curtus*, *Trochammina squamata*), while a few exhibited wider and more distal occurrences (e.g., *Elphidium excavatum* and *Elphidium subarcticum*). These differences point to variations in the Merrimack River outflow and its effects upon water column nutrient delivery, productivity, and organic matter flux over the past six decades. Other mitigating factors affecting benthic foraminiferal distributions may include increased seafloor disturbance from strong winter storms or fishing activity.

Species richness and evenness peak at the delta break, coincident with low species dominance at about 50-m depth. Q-mode cluster analyses show three distinct assemblages: “shallow” (≤ 30 -m water depth), “deep” (≥ 40 m), and “delta edge” (~ 50 m). There are no apparent correlations between foraminiferal distributions and deltaic bedforms or sediment type. This implies that foraminiferal distributions are controlled by other environmental variables other than grain size, such as food availability.

INTRODUCTION

OBJECTIVE

In early September 2005, sediment samples and the microfossils within were collected along two depth transects across the Merrimack River paleo-delta in the Merrimack Embayment of the western Gulf of Maine to characterize offshore sand and gravel resources for potential use as construction aggregate and beach replenishment (Fig. 1). The project was a pilot study funded by the former Minerals Management Service, U.S. Department of the

Interior. Researchers at Boston University characterized these marine resources using geophysical and sedimentological techniques, while researchers at the University of Massachusetts Amherst used micropaleontology techniques. This project presents and interprets the collected biotic data in light of the geophysical and sedimentological data published elsewhere (e.g., Hein et al., 2007, 2012; Barnhardt et al., 2009). It demonstrates how micropaleontological analyses can complement geophysical analyses to provide information unavailable through geophysical techniques. Most importantly, this project illustrates the utility of studying benthic foraminifera as a proxy for substrate conditions pre- and post-sediment disruption (e.g., from offshore mining of sand and gravel resources). Thus, benthic foraminifera can be used to gauge biotic recovery by analyzing recolonization trends.

PROXIES

This study uses benthic foraminifera as a biotic and environmental proxy to study the benthic ecology of the Merrimack Embayment. Benthic foraminiferal distributions on the continental shelf are influenced by factors such as water temperature, depth, salinity, dissolved oxygen, grain size of seafloor sediments, and food availability (e.g., Murray, 1991; Jorissen et al., 1995; Goldstein, 1999; Jorissen, 1999; Sen Gupta, 1999; Leckie & Olsen, 2003). In general, their distributions trend parallel to the coast with both increasing water depth and distance from the shore (e.g., Phleger & Parker, 1951; Phleger, 1960; Upshaw & Stehli, 1962; Walton, 1964; Gibson & Buzas, 1973; Murray, 1973, 1991; Culver & Buzas, 1981; Poag, 1981; Culver, 1988). Foraminiferal abundances also vary seasonally (e.g., Korsun & Hald, 2000; Murray & Alve, 2000; Scott et al., 2003). Thus, although the data presented in this study represent a one-day snapshot of the seasonal progression of changing foraminiferal assemblages in the Merrimack Embayment, useful trends can be observed.

In this study, benthic foraminiferal distributions and abundances are coupled with geophysical and sedimentary analyses to: 1) develop a model of foraminiferal distribution patterns to assess depositional environments and establish a modern base line of the data; 2) confirm geophysical techniques such as side-scan sonar to delineate sedimentary facies and grain-size distribution; and 3) test the applicability of foraminifera as a biotic monitor of post-disturbance ecosystem recovery (e.g., following offshore sand mining operations; Scott & Lipps, 1995; Yanko et al., 1999; Dabbous & Scott, 2012).

A similar study was conducted by Phleger (1952) and Parker (1952) over 60 years ago, which spanned the western Gulf of Maine from Cape Ann to Portsmouth, New Hampshire, and seaward from the coastline to Jeffreys Ledge. They examined foraminiferal abundances and distributions using 738 seafloor sediment samples collected

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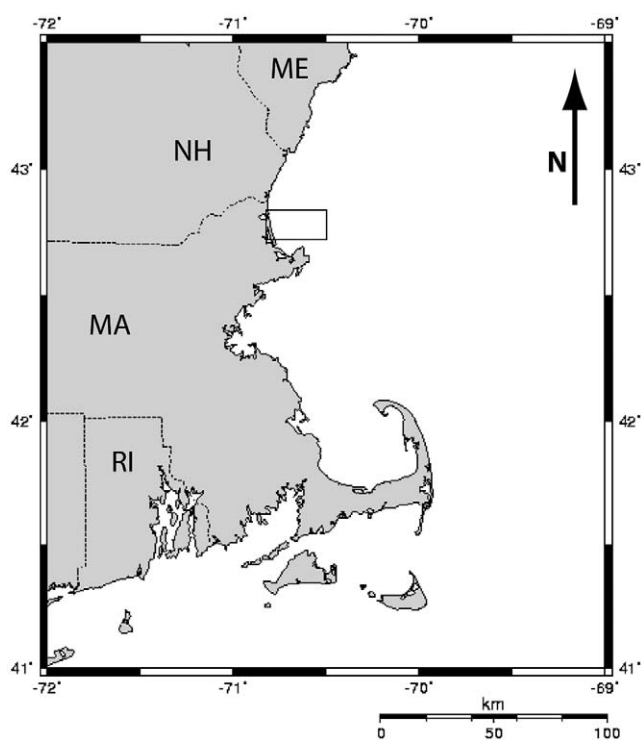


FIGURE 1. Merrimack Embayment study area within black rectangle (map from http://www.aquarius.geomar.de/omc/make_map.html).

mostly during the summer of 1946. Here we compare the foraminiferal distribution patterns observed today to a small portion of the Phleger and Parker studies. The results presented here will serve as a pilot study for future research across the Gulf of Maine.

GEOGRAPHIC LOCATION, FORM, AND HISTORY

The Merrimack Embayment stretches from Cape Ann, Massachusetts, to Hampton, New Hampshire. The most prominent submarine feature of the embayment is the “paleo-delta” of the Merrimack River (hereafter referred to as the delta). The delta extends approximately 8 km east of the mouth of the Merrimack River, with its edge marked by a change in seafloor slope, currently at a water depth of ~50 m (Oldale et al., 1983). The delta is approximately 20-km long from north to south and 7-km wide from east to west (Oldale et al., 1983; Fig. 2).

The Merrimack River delta and its braided river plain undergo active reworking by waves, currents, and tides, producing four distinct sedimentary zones along the inner shelf (Hein et al., 2007). The first zone is centered east of the river mouth. Here the seafloor is a featureless sand sheet that ranges in thickness from 0 to <50 cm, and composed of coarse-grained sands and fine gravels (Figs. 3 and 4). In the remaining three zones, the sand sheet undergoes active reworking and varies in thickness from <1 m to ~9–10 m,

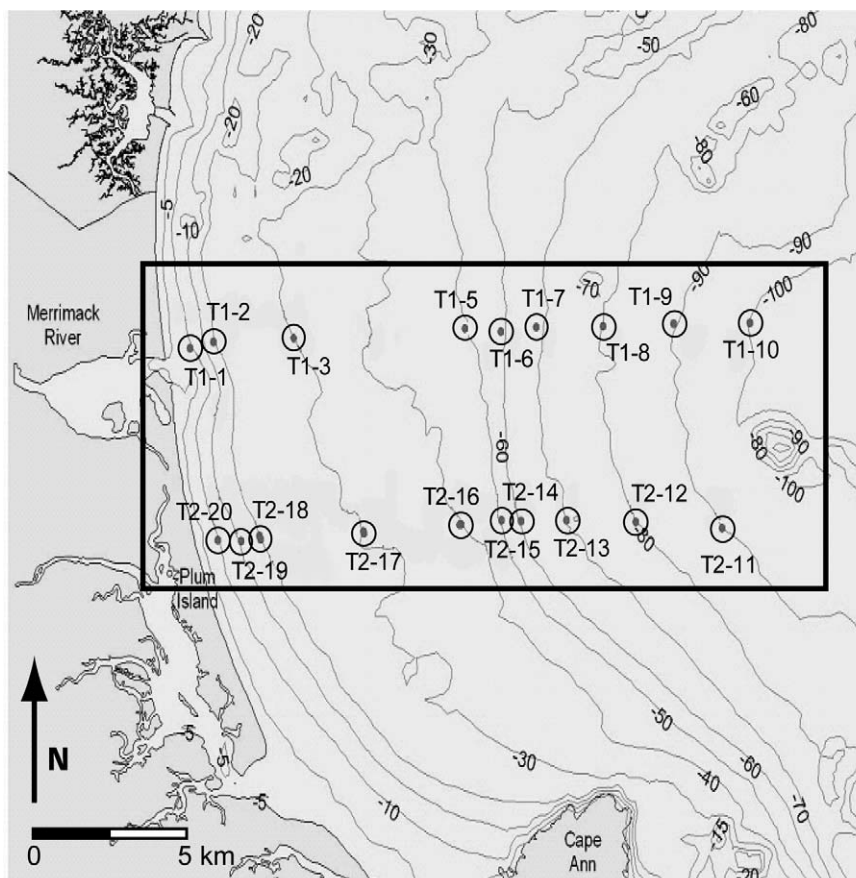


FIGURE 2. Merrimack Embayment station locations for Transect 1 (T1, stations 1–10) and Transect 2 (T2, stations 11–20) with bathymetry lines in meters (image provided by L. Ward, University of New Hampshire).

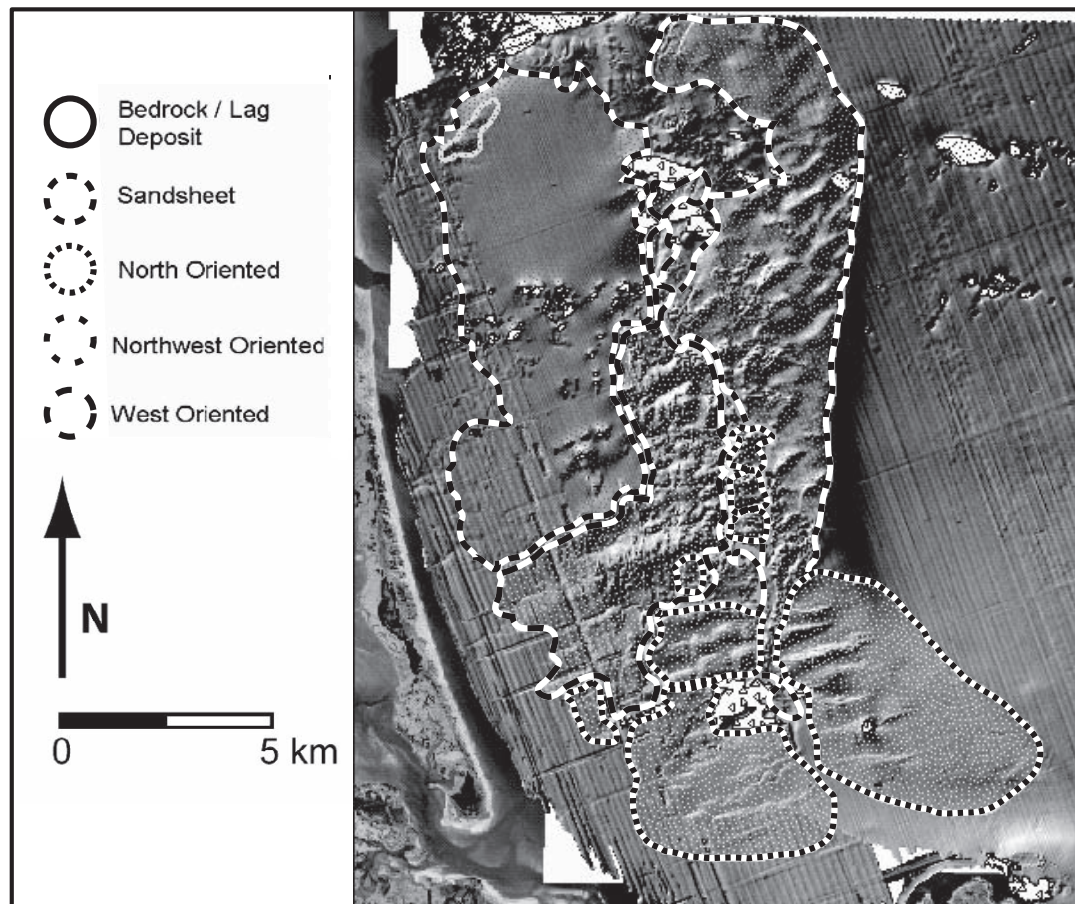


FIGURE 3. Merrimack Embayment bedform types and locations, modified from Hein et al. (2007, 2013).

with the thickest deposits along the shoreface and offshore of southern Plum Island and Castle Neck (Barnhardt et al., 2009). The second zone is comprised of asymmetrical bedforms orientated (dipping) northwest. These bedforms are located near the delta break, have average wave lengths of 500 m and average amplitudes of 1.9 m. The third zone is located to the south and inshore. It has westward orientated asymmetrical bedforms, with average wave lengths of 250 m and amplitudes of 1 m. The fourth zone is farther south, ~4-km north of Cape Ann. Here, bedforms are orientated north, have average wave lengths of 500 m and average amplitudes of 1 m (Hein et al., 2007).

During the last glacial period, the coastline of northern New England was depressed by the overlying ice sheet. Deglaciation and global sea-level rise resulted in flooding (transgression) and deposition of glaciomarine sediments in these coastal areas (e.g., Bloom, 1963; Oldale et al., 1983; Kelley et al., 1992). Subsequent crustal rebound forced a relative sea-level fall and the coastline to advance seaward (regression). Sea level reached a regional lowstand approximately 13,000–14,000 ybp at ~45 m below modern sea level, providing for the deposition of a lowstand delta (Oldale et al., 1983). By 3000–5000 ybp, continued sea-level rise had fully drowned the delta, but slowed enough to permit the establishment of barrier beaches such as Plum Island (Kelley et al., 1992; Hein et al., 2012).

OCEANOGRAPHIC CONDITIONS

Sea-surface temperatures in the Merrimack Embayment range from ~4°C in February to 17–18°C in August (Pathfinder, 2005). In February and March, the water column is isothermal. By August, it is strongly stratified, with the thermocline at 40–50 m and bottom temperatures at ~5.5°C (Parker, 1952; Phleger, 1952; Pathfinder, 2005).

Seasonal changes in salinity are generally uniform across the study area (Parker, 1952; Phleger, 1952; GoMOOS, 2006). The Gulf of Maine Ocean Observing System (GoMOOS) Buoy B (Station 44030, Buoy B0102) is located 50-km north of the Merrimack River on the western Maine shelf and records bottom waters consistently saltier than those in the upper water column (GoMOOS, 2006). In winter, the water column is isohaline and has a maximum salinity of ~31.75–32.50‰. Surface-water salinity drops to 29‰ from early spring to early summer, increasing to ~30.5–31‰ by October, and becoming isohaline again by early December. Bottom-water salinity changes from 31.5‰ in mid-summer to 32.5‰ during the winter (GoMOOS, 2006).

Unlike temperature and salinity, Chlorophyll a (ChlorA) varies greatly, both seasonally and spatially across the study area (SeaWifs, 2005). Seasonal ChlorA values in the study area are at a low in February and August, ~2–3 mg/m³ near shore and ~1 mg/m³ to the eastern limit of the study area.

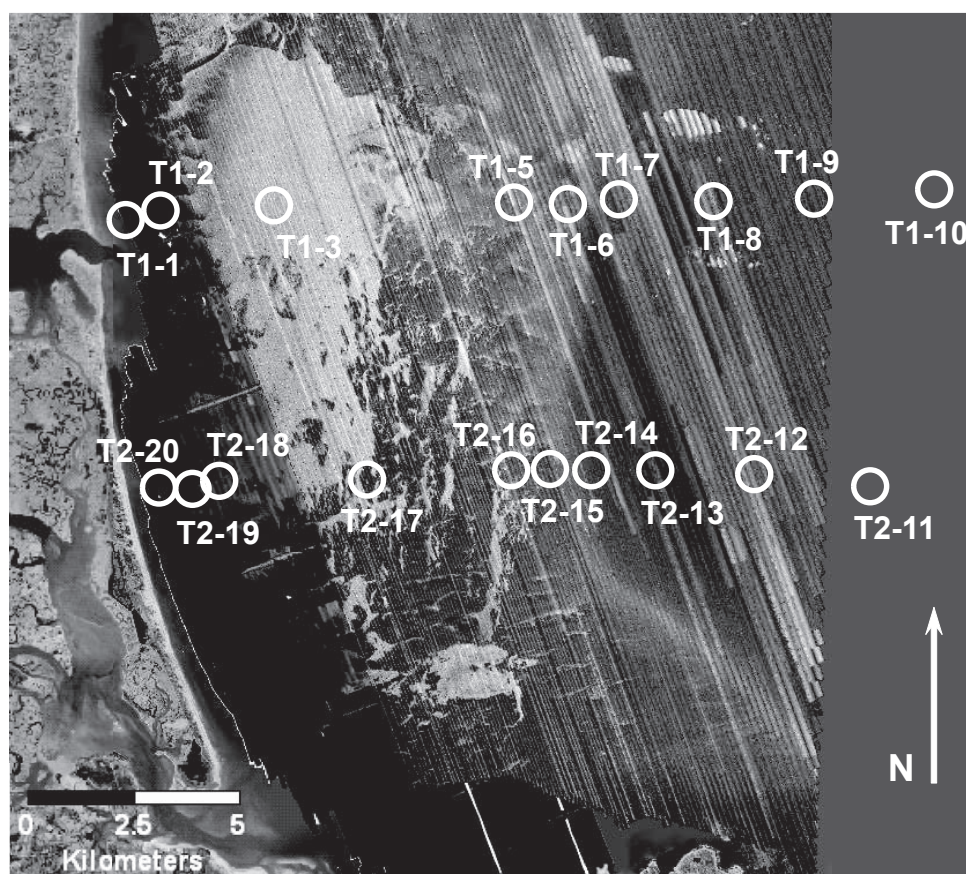


FIGURE 4. Merrimack Embayment side-scan sonar and station locations (circles) for this study, modified from Hein et al. (2007, 2013).

Peak ChlorA concentrations occur in April ($\sim 10 \text{ mg/m}^3$), reach a low by August, and then increase to an intermediate high value in October.

Waves are predominately from the northeast and are particularly strong during winter storms (Hein et al., 2012). As a result, longshore transport along the barrier islands of the Merrimack Embayment, particularly Plum Island, is primarily to the south. In addition, the deeper water, southward flowing Northern Shelf (coastal) Current produces a counter-clockwise gyre within the Gulf of Maine (Buzas & Culver, 1980). Bottom currents along the shallow shelf in the Merrimack Embayment are more uncertain. The GoMOOS Buoy B (western Maine shelf) has recorded bottom currents of 20–30 cm/sec at 60-m depth during spring tides and higher speeds during storms (Hein et al., 2007). Bottom currents and their speed across the Merrimack River delta sand sheet are unknown.

METHODS

SAMPLE RECOVERY

On September 6, 2005, seafloor sediment samples were collected with a small box corer from 19 sites (1 sample/site) along two parallel east–west transects across the inner shelf and the Merrimack River delta (Figs. 1 and 2). The northern transect was located east of the Merrimack River mouth, while the southern transect was located 5 km to the

south, offshore from Plum Island. The two transects sampled the Merrimack River delta plain, break, and front, which ranged in character from gravel and coarse sand to mud. Sampling every 10 m of water depth out to 103 m, the northern transect yielded nine samples and the southern transect, 10. The samples were processed and analyzed for their foraminiferal characteristics by researchers at the Massachusetts Geological Survey and the Department of Geosciences, University of Massachusetts Amherst. Geophysical and sedimentological analyses were completed by researchers at Boston University. The data obtained in this study were compared to those collected by Phleger (1952) and Parker (1952). To facilitate this comparison of foraminiferal distributions, 15 sites of the 738 studied by Phleger (1952) and Parker (1952) in the Gulf of Maine are regarded as “comparable” to the 19 sites examined in this study because of their close geographic proximity, although they are not an exact match (Fig. 5). Some sites have offsets ranging from tens of meters up to 2 km. The concept of “comparable” also tries to minimize differences in water depth and sediment type that exist between the Phleger (1952) and Parker (1952) sites and those in this study. Differences in location, water depth, sediment type, time of collection, and other factors need to be kept in mind when making comparisons between the two studies.

Sediment from the top 2 cm and 2–5-cm depth was collected from each box core sample for foraminiferal analysis. These subsamples ranged in volume from ~ 100 –

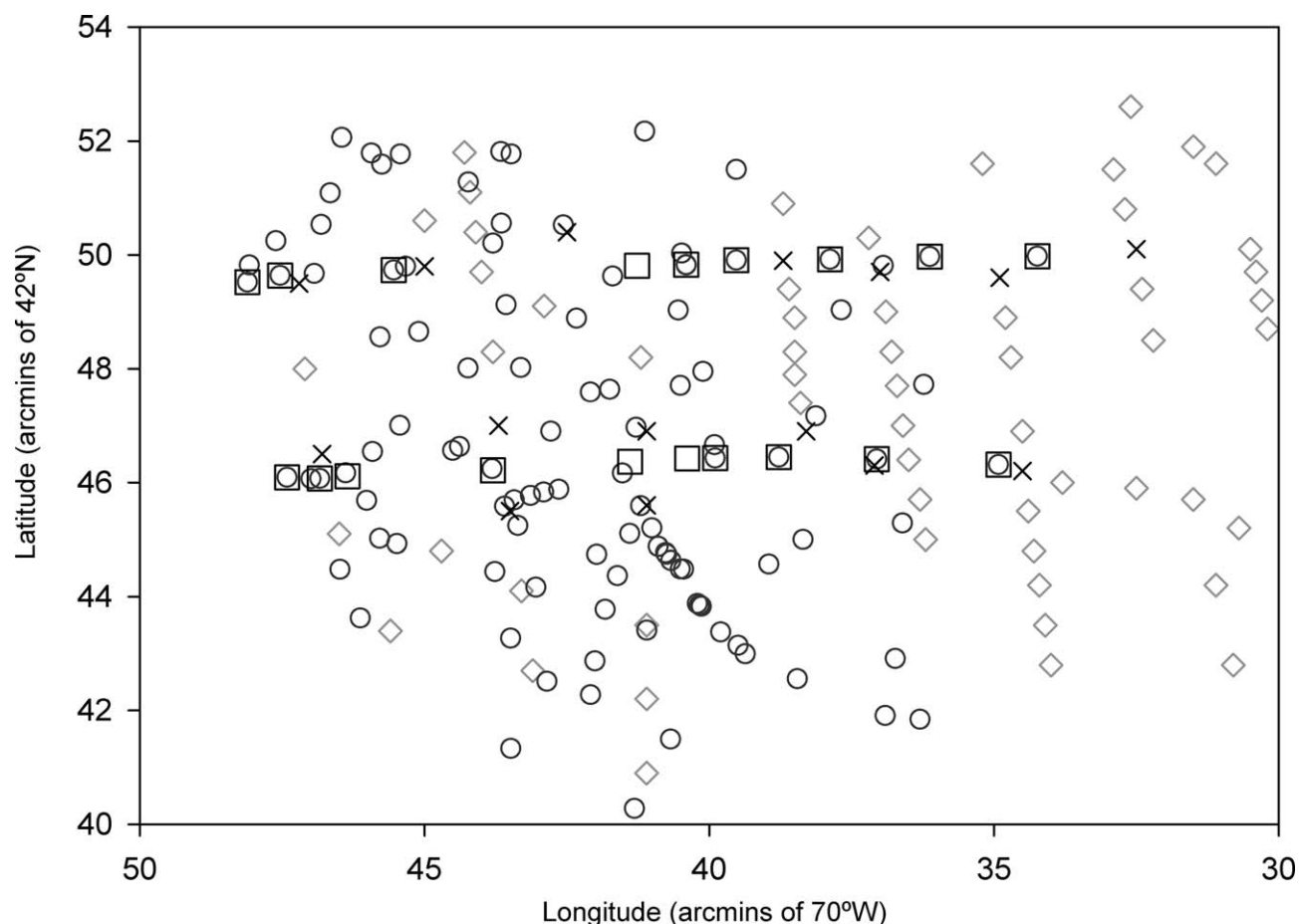


FIGURE 5. Sample sites for the Merrimack Embayment: diamonds: Phleger (1952) and Parker (1952) sample sites; circles: Boston University sample sites; squares: this study; x-symbols: Phleger (1952) and Parker (1952) sample sites that are “comparable” to this study.

200 cm³, and were placed in 250-cm³ Nalgene™ bottles. To preserve the foraminifera within each sample, a 4% formalin solution was added to all bottles and shaken. At least 25 gm of borax (twice as much for the muddier samples) was added to each sample bottle to make an alkaline solution. The bottles were shaken again, and then stored in a freezer until analysis.

In their study, Phleger (1952) and Parker (1952) differentiated between living and dead foraminifera. They found a “good correlation” between the geographic distributions of live foraminiferal tests of each species and all tests of that species (for sediments containing mud). In light of those results, we did not take steps to differentiate between living and dead foraminifera.

TABLE 1. Ten most common benthic foraminifera from the Merrimack Embayment. Notes (left-right): column 2, ten most common benthic foraminiferal species identified in Phleger (1952) and Parker (1952), ranking based on a limited set of sites that are geographically proximal to the sites in this study; column 4, ten most common benthic foraminiferal species identified in this study; column 6, ranking if acidic samples in this study are removed from the data. Calcareous species are in bold.

Rank	Phleger (1952) and Parker (1952): 10 most common species (9079 tests)	% tests	This study: 10 most common species (all samples; 5749 tests)	% tests	This study: 10 most common species (samples having >7 pH; 3912 tests)	% tests
1	<i>Eggerella advena</i>	39	<i>Eggerella advena</i>	14	<i>Eggerella advena</i>	15.5
2	<i>Elphidium subarcticum</i>	7.2	<i>Adercotryma glomeratum</i>	13	<i>Elphidium subarcticum</i>	12.9
3	<i>Saccammina atlantica</i>	6.8	<i>Elphidium subarcticum</i>	9	<i>Elphidium excavatum</i>	8.5
4	<i>Textularia torquata</i>	6.7	<i>Textularia torquata</i>	7.4	<i>Saccammina atlantica</i>	5.4
5	<i>Elphidium excavatum</i>	5.5	<i>Elphidium excavatum</i>	5.7	<i>Cibicides lobatulus</i>	4.8
6	<i>Reophax scottii</i>	4.6	<i>Spiroplectammina biformis</i>	5.2	<i>Adercotryma glomeratum</i>	4.2
7	<i>Trochammina squamata</i>	3.6	<i>Saccammina atlantica</i>	5.0	<i>Textularia torquata</i>	3.9
8	<i>Spiroplectammina typica</i>	3.6	<i>Spiroplectammina typica</i>	3.8	<i>Reophax scottii</i>	3.8
9	<i>Eponides frigidus</i> (Cushman)	3.6	<i>Reophax scottii</i>	3.6	<i>Buccella frigida</i>	3.5
10	<i>Cibicides lobatulus</i>	3.3	<i>Cibicides lobatulus</i>	3.2	<i>Quinqueloculina</i> spp.	2.8

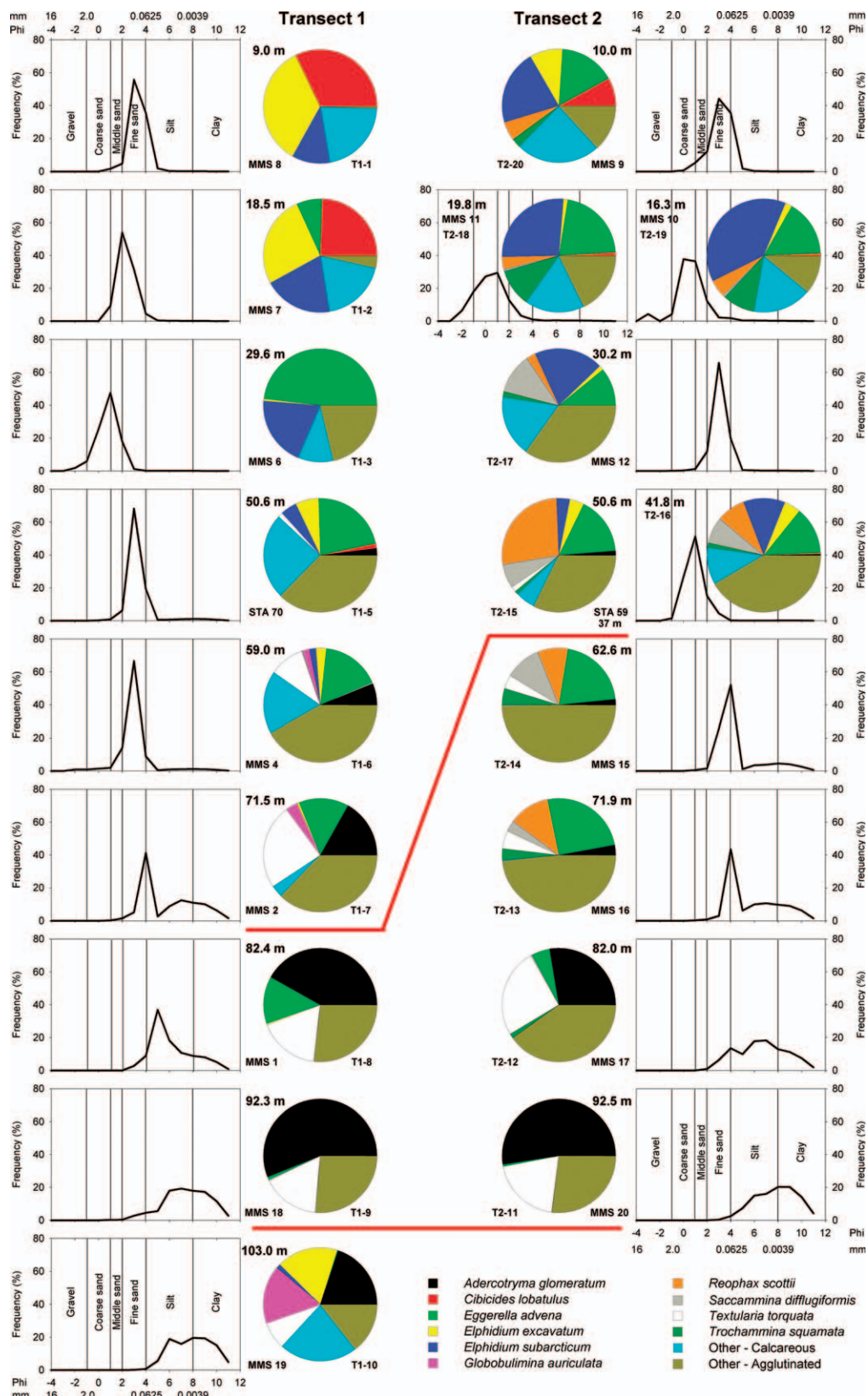


FIGURE 6. Foraminiferal assemblages of the Merrimack Embayment, derived from the T-samples collected in the two transects shown in Figure 2. The water depth (m) and abundances of up to ten species are presented for each sample; other species are grouped and depicted as “Other-Calcareous” or “Other-Agglutinated.” Red lines enclose the six samples that were subject to dissolution. Grain-sizes depicted in mm and phi units (data provided by C. Hein). Note: delta plain (topsets <50-m depth), delta break (50–60 m), delta front (foresets/bottomsets >60 m) MMS = Minerals Management Service, STA = Station.

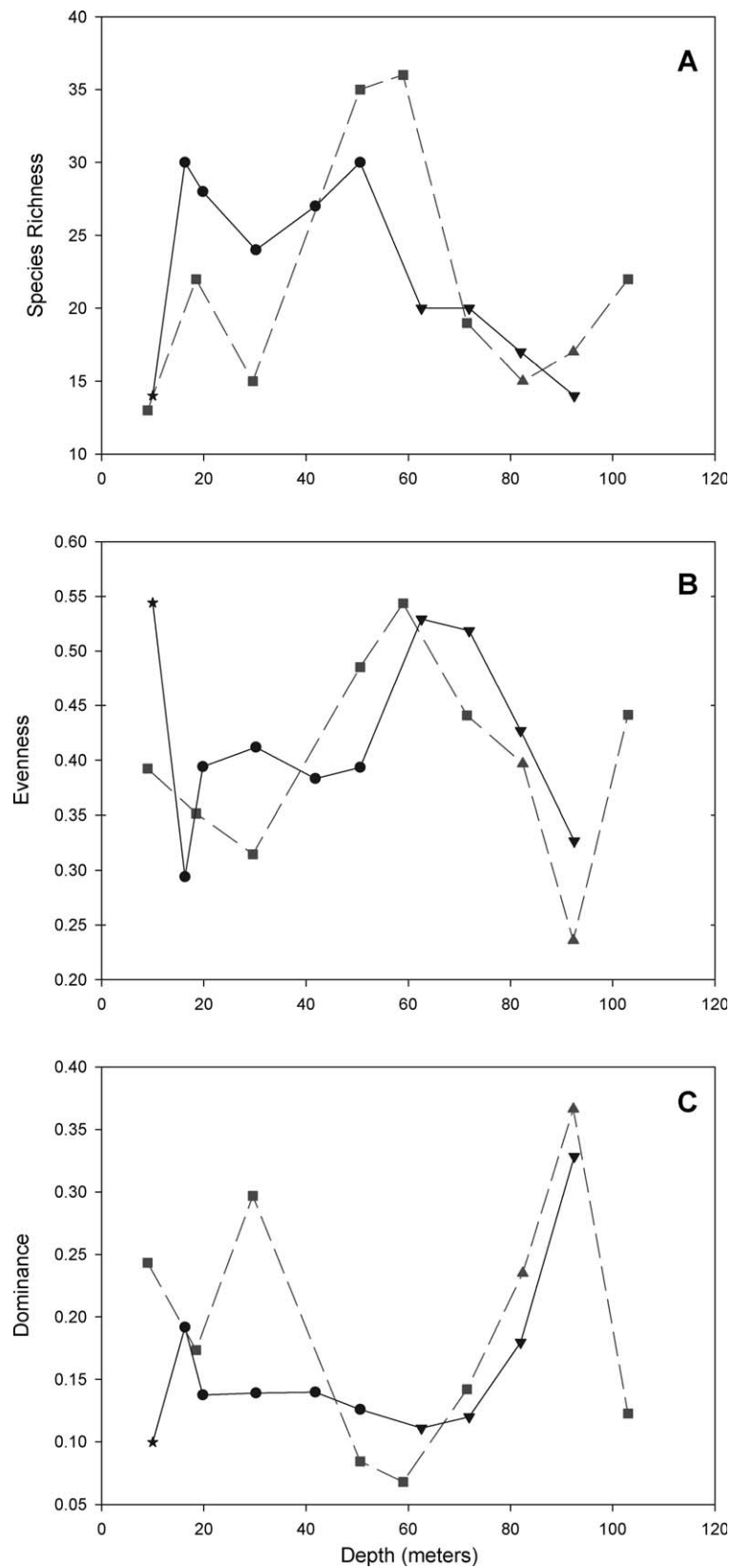


FIGURE 7. **A** Benthic foraminiferal species richness, **B** species evenness, and **C** species dominance for the Merrimack Embayment. Transect 1: dashed line, squares, and up triangles. Transect 2: solid line, filled circles, and down triangles. Triangles: acidic samples (affected by suspected dissolution). Star: sample not statistically robust (see text).

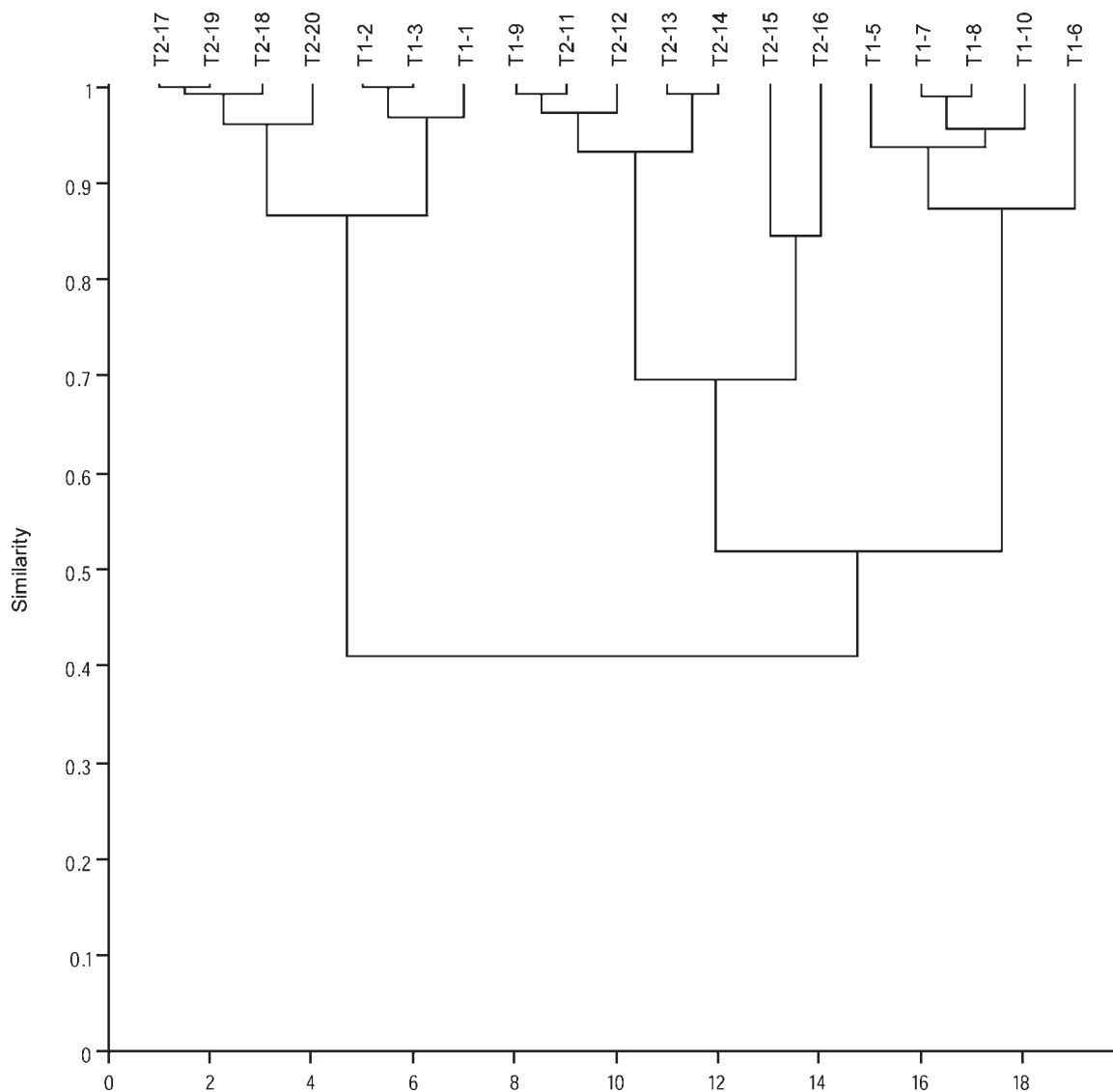


FIGURE 8. Cluster analysis dendrogram, Raup-Crick measure, showing three distinct assemblages: "shallow" (≤ 30 -m water depth), e.g., Sites T1-1, T1-2, T2-19; "deep" (≥ 40 m), e.g., Site T1-10; and "delta edge" (~ 50 m), e.g., Sites T1-5, T2-15.

After thawing in the laboratory, all samples were measured for pH, and soaked in a 10% solution of hydrogen peroxide (H_2O_2) for several days. Six samples had pH levels < 7 after thawing; they were immediately adjusted to a pH of at least 8 by the addition of Borax prior to soaking. The sediment mixture was then washed over a $63\text{-}\mu\text{m}$ sieve and the residues were dried in an oven at 60°C . The residuals were then passed through a 2-mm sieve. The sand-sized residues ($63\text{--}2000\ \mu\text{m}$) were later examined for species present (species richness), relative abundance, and preservation.

The residuals of each processed sample were repeatedly split with a microsplitter until a volume of sediment was obtained that, when spread evenly onto a picking tray, produced a single layer of particles. All foraminiferal tests on the tray (both benthic and planktic) were then removed and affixed to a gummed microscope slide for

identification and counting. Other biogenic particles on the tray (e.g., macro- and microfossils), as well as inorganic particles (mineral grains, etc.), were transferred to the gummed slide in representative numbers. Because the foraminifera in any one tray were typically scarce, the above process was repeated until at least 300 foraminiferal tests were collected from each sample. Broken tests that comprised more than half of the test size were counted as a whole test. In some cases, a large fraction of the sample or its entire volume was examined to attain at least 300 tests. One sample, T2-20 (the site closest to shore), yielded only 75 tests.

Species richness, evenness, and dominance are assemblage indices that provide information about the environment where a sediment sample was collected. These indices were used to complement geophysical and sedimentological analyses of the Merrimack River delta.

TABLE 2. Species diagnostic of the Merrimack River paleo-delta environments. Calcareous species are in bold.

Environment	Diagnostic species
Delta plain (topsets, coarse to fine sand): <50-m water depth, Transect 1	<i>Cibicides lobatulus</i> , <i>Elphidium excavatum</i> , <i>Discorbis columbiensis</i> (Cushman)
Delta plain: <50 m, Transect 2	<i>Elphidium subarcticum</i> , <i>Saccammina atlantica</i> , <i>Trochammina squamata</i>
Delta break (fine sands): 50–60 m, Transect 1	<i>Buccella frigida</i> , <i>Globocassidulina islandica</i> (Nørvang), <i>Glomospira gordialis</i> Cushman & Ozawa
Delta break: 50–60 m, Transect 2	<i>Reophax scottii</i> , <i>Reophax curtus</i> , <i>Saccammina difflugiformis</i>
Delta front (foresets/bottomsets, muds): >60 m, Transect 1	<i>Adercotryma glomeratum</i> , <i>Textularia torquata</i> , <i>Elphidium excavatum</i> , <i>Globobulimina auriculata</i>
Delta front: >60 m, Transect 2	<i>Adercotryma glomeratum</i> , <i>Eggerella advena</i> , <i>Textularia torquata</i>

Species evenness was determined by the relationship:

$$E = e^H / S$$

(a rearrangement of the SHE index for E; e.g., Buzas {Hayek, 1998),

where E is the species evenness index; e, the natural log; H, the Shannon-Weiner diversity index; and S, the number of species (Wakefield, 2003). The Shannon-Weiner diversity index in turn is:

$$H = - \sum_{i=1}^S (p_i \ln p_i),$$

where S is the number of species and p_i , is the proportion of the i th species (Wakefield, 2003).

Species dominance was determined using the Simpson index:

$$D = \sum_{i=1}^S [n_i(n_i - 1) / N(N - 1)],$$

where D is the Simpson dominance index; S, the number of species; n_i , the number of individuals in the i th species; and N, the total number of individuals. Additional statistical analyses were made using the PAST software program

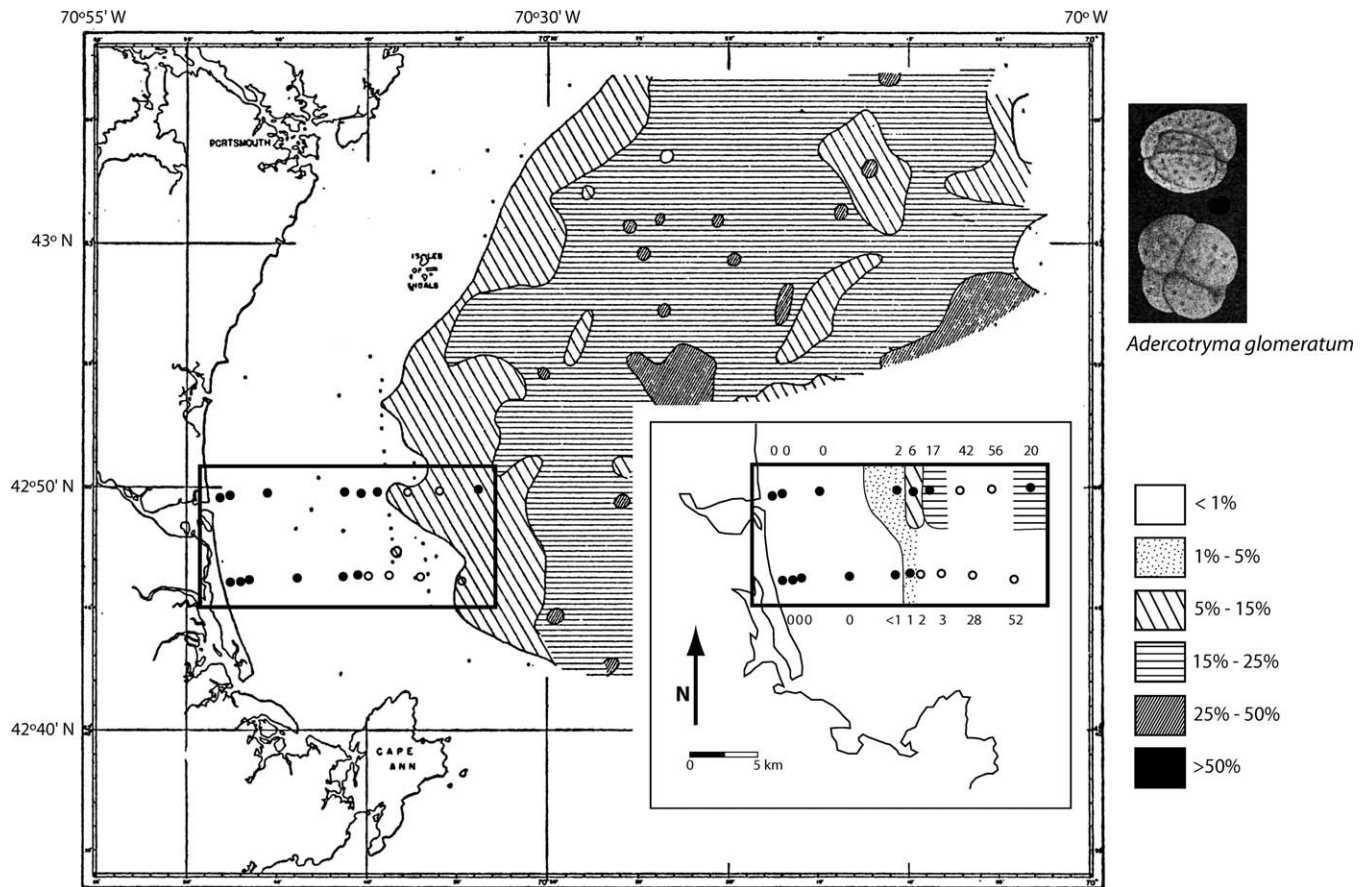


FIGURE 9. Distribution of *Adercotryma glomeratum* in percent of total population of benthic foraminifera. Large map depicts 1946 data modified from Phleger (1952) and 2005 station locations from this study, shown as circles within rectangle. Inset map depicts the 2005 study area (rectangle), within which closed circles depict sites where sample data were contoured and open circles depict sites where data were not contoured due to suspected sample dissolution. Percent abundances at each site are shown above and below the 2005 study area inset rectangle.

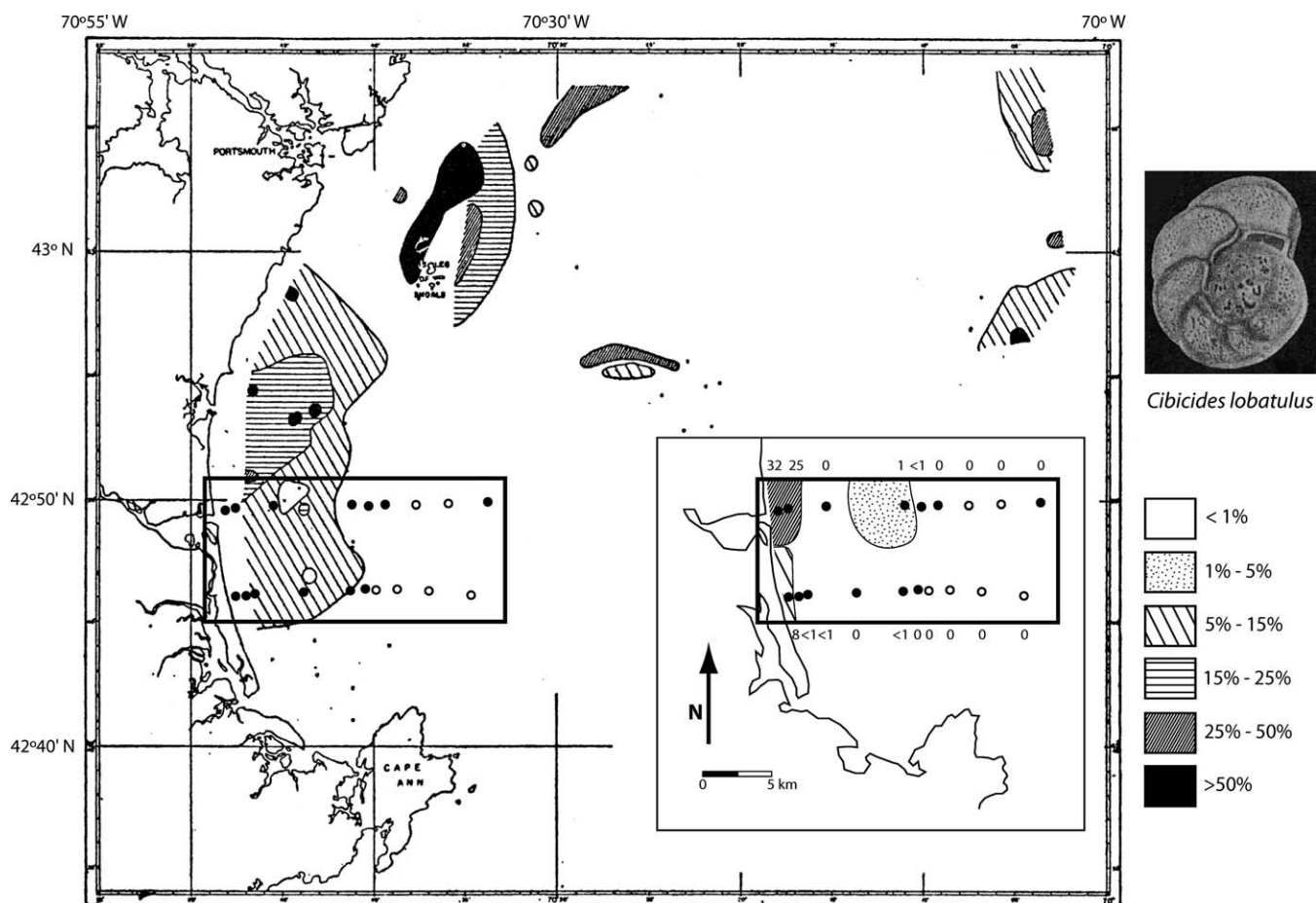


FIGURE 10. Distribution of *Cibicides lobatulus* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

(Ryan et al., 2007), including multivariate techniques such as Q-mode cluster analysis.

Distributions of key species are briefly discussed in the Results and Discussion section, while species recognition is discussed in Appendix 1. The species observed in each sample and their abundances are recorded in Appendix 2.

RESULTS AND DISCUSSION

SAMPLE PRESERVATION AND DISSOLUTION

Test preservation was very good to excellent in all samples. Some calcareous tests were glassy in appearance and/or bright green in color due to the recent assimilation of chloroplasts from photosynthetic organisms (e.g., diatoms). Tests of agglutinated and calcareous species were typically complete. Broken tests or tests that appeared to be reworked were uncommon (i.e., having a worn/degraded or stained appearance, perhaps reworked during post-Last Glacial Maximum transgression, and/or being transported from a different locality).

Calcium carbonate (calcite) tests are susceptible to dissolution when exposed to acidic conditions. In spite of efforts to avoid post-collection test dissolution (by adding borax to boost sample pH before freezing), it is very likely

that several samples in this study were affected by dissolution. After thawing, it was discovered that six samples were acidic, including two samples from Transect 1 (Sites T1-8 and 9) and four samples from Transect 2 (Sites T2-11 through T2-14). These samples were muddier and more organic rich than shallower samples. It is likely that the decay of organic compounds in these samples produced acids that overwhelmed the buffering capacity of the added preservative. The acidic conditions in these samples affected delicate and/or smaller calcareous species more than larger and/or robust species. The net effect of dissolution on assemblage analysis is the alteration of the relative abundance of one species to another. The result is an increased percent abundance for arenaceous (i.e., agglutinated) species and also larger and/or more robust calcareous species relative to smaller and more delicate ones (Table 1).

The deepest sample (Transect 1, Site T1-10, 103 m) was alkaline after thawing, and calcareous species, as well as agglutinated ones, were presumably not affected by dissolution. Using Site T1-10 as a guide, the following calcareous species, at a minimum, are likely missing in samples affected by low pH (Fig. 6) due to dissolution: *Bulimina aculeata* d'Orbigny; *Buliminella complanata* (Egger); *Buccella frigida* (Cushman); *Elphidium excavatum* (Terquem); *Elphidium subarcticum* Cushman; *Epistominella vitrea* Parker; *Globobulimina auriculata* (Bailey); *Globocas-*

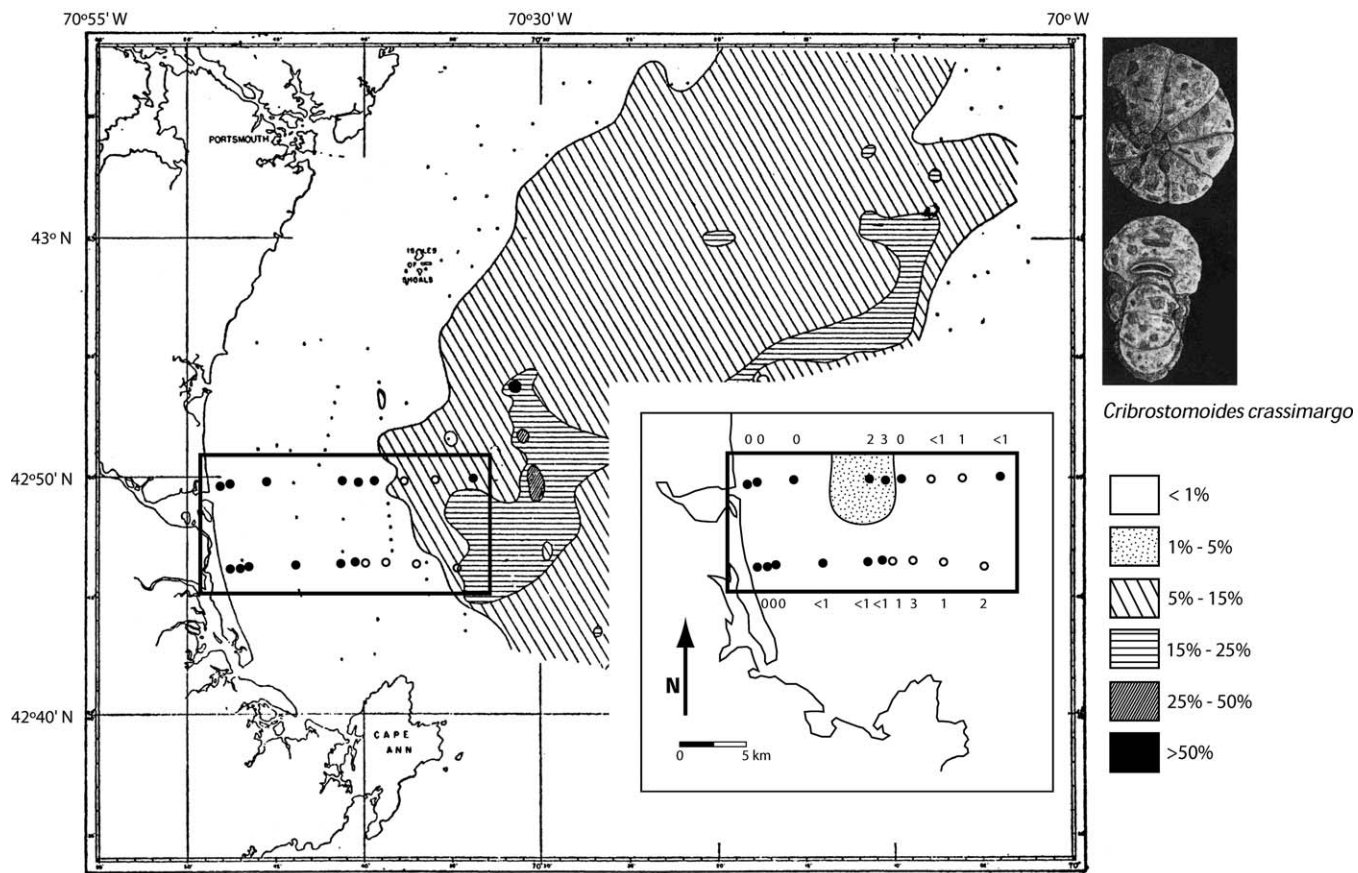


FIGURE 11. Distribution of *Cribrostomoides crassimargo* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

sidulina algida (Cushman); *Nonionella auricula* Heron-Allen & Earland; and *Nonionellina labradorica* (Dawson).

Despite the effects of dissolution, this study demonstrates that the data presented here are robust. Several important trends are documented and many useful conclusions are drawn. Thus, the findings of this study were minimally impacted by sample preservation. Nonetheless, this study considers only data from samples that were alkaline after thawing.

FORAMINIFERAL ASSEMBLAGES

Species Richness

Species richness represents the number of species in a sample. In general, low sample richness implies harsher environments, where one or a few species are better adapted for survival. A sample with high richness implies an environment that is less severe, where many species are able to coexist on a more equal basis. Species richness can also be affected by preservation, including the selective dissolution of calcareous species (discussed above), as well as seasonal changes in foraminiferal assemblages.

Along Transect 1, species richness was lowest near shore with 13 species at 9 m, peaked with 36 species (59 m, T1-6), and then decreased to 22 species at the deepest site (T1-10; Fig. 7A). The peak in species richness coincides with the delta break at ~50 m, and the change in seafloor sediments

from sand to mud occurs at deeper than 60 m (Fig. 6). Species richness along Transect 2 has two peaks of 30 species at 16.3 m and 50.6 m before decreasing steadily to 14 species at 92.5 m. Like Transect 1, the more distal peak in species richness along Transect 2 coincides with the delta break and roughly coincides with an increase in seafloor mud content below 60 m. The abrupt decrease in Transect 2 richness below 50.6 m is an artifact of excluding those samples which were acidic at the time of processing.

Foraminifera were extremely scarce in the near-shore sample collected from Transect 2, Site T2-20 (only 75 tests). To statistically represent foraminiferal abundances in a sample, the collection of ~300 tests is more suitable (e.g., Buzas, 1990). Thus, the number of species observed and their relative abundances in this sample are not considered to be completely representative of the in situ assemblage.

A comparison of richness between this study and Phleger (1952) and Parker (1952) can only be accomplished qualitatively due to differences in geographic area. Sixty-two benthic foraminiferal species were identified in this study, while Parker (1952) described 74 species across a broader area of the Gulf of Maine.

Species Evenness

Species evenness is a gauge of how evenly the total number of foraminifera identified in a sample is distributed

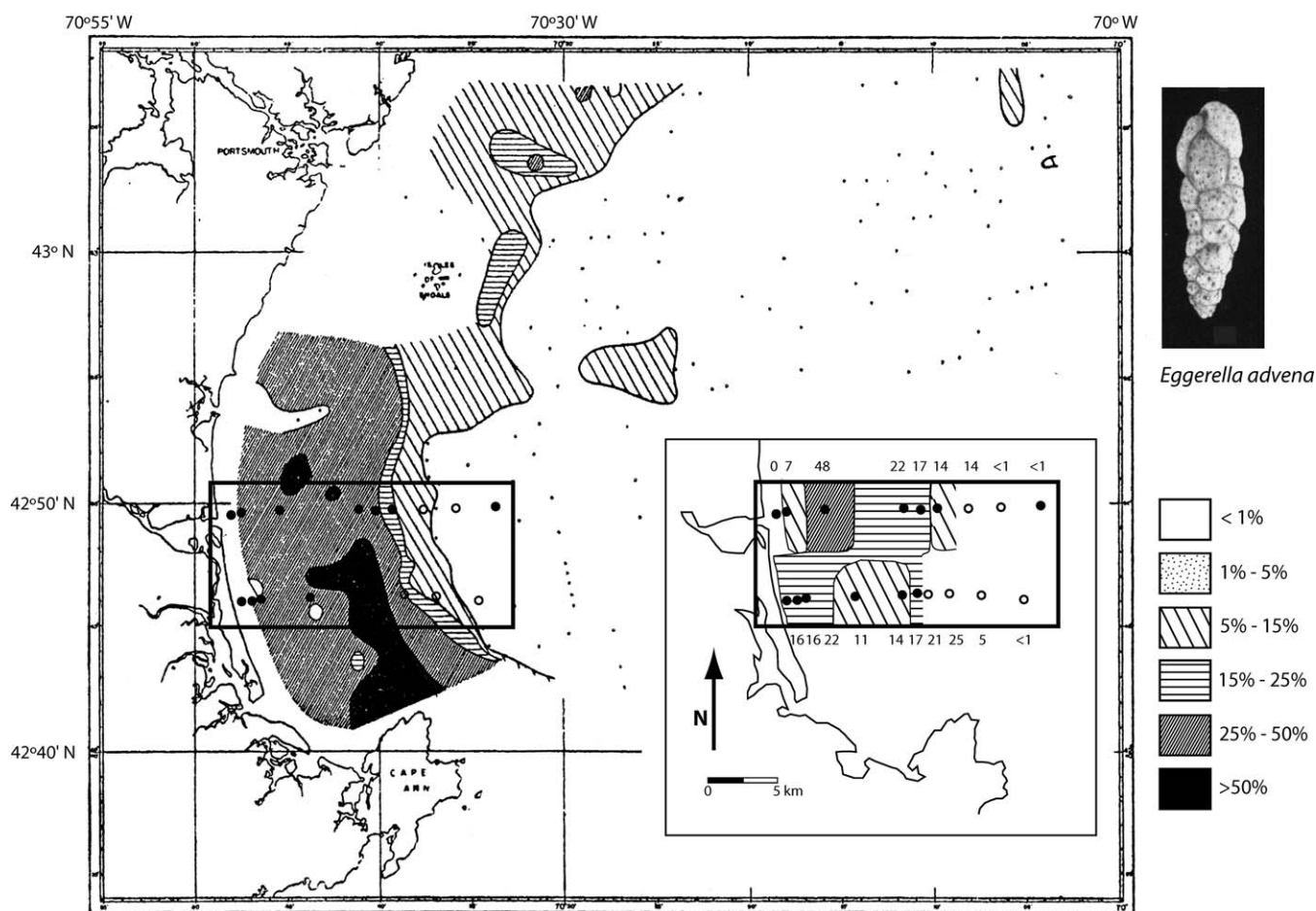


FIGURE 12. Distribution of *Eggerella advena* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

amongst the species present. In general, a graph of species evenness follows that of species richness when plotted against water depth (Fig. 7B).

Foraminiferal assemblages along Transect 1 tend to be more evenly distributed in samples that were recovered near the delta break, at ~50–60 m. For Transect 2, samples collected deeper than 50.6 m are biased by dissolution of the calcareous taxa. The high degree of evenness observed at the shallowest Transect 2 site (T2-20) coincides with the statistically low number of tests collected from that sample.

Species Dominance

Species dominance is a measure of how the abundance(s) of one or several species dominates the other species in a sample. Species dominance and species richness (and species evenness) typically have an inverse relationship to one another. A sample obtained in an environment with low richness (and low evenness) is more likely to have a strongly dominant species (or several species) than a sample recovered from a highly rich environment. Such conditions of high dominance, low richness, and low evenness are typically associated with stressed environments or differential preservation.

Transect 1 species dominance reaches a low point at the delta break (Fig. 7C), nearly the exact inverse to the high

point in species richness at the same location. For Transect 2 dominance is generally low (ignoring the biased samples T2-11 through T2-14 and T2-20). This roughly matches the unbiased samples that exhibit relatively high richness along the shallow-water segment. Yet the Transect 2 dominance curve is mostly unchanged compared to the same interval for species richness.

STATISTICAL ANALYSES

The data in this study were analyzed using Q-mode cluster analysis that uses percentage foraminiferal abundance data from each sample to identify groups of samples having a mathematical commonality to one another (Ryan et al., 2007). The technique is useful because it can reveal statistical grouping of samples that may represent actual groupings in the environment (i.e., biotopes such as delta plain, delta break, and delta front).

Only species that accounted for >1% of the population in at least one sample were used for the cluster analysis. Several clustering measures such as Raup-Crick were employed and each measure produced similar dendrograms (Fig. 8). Because the PAST program revealed consistent trends in the data, it is assumed that the clusters are true representations of the data rather than artifacts of the

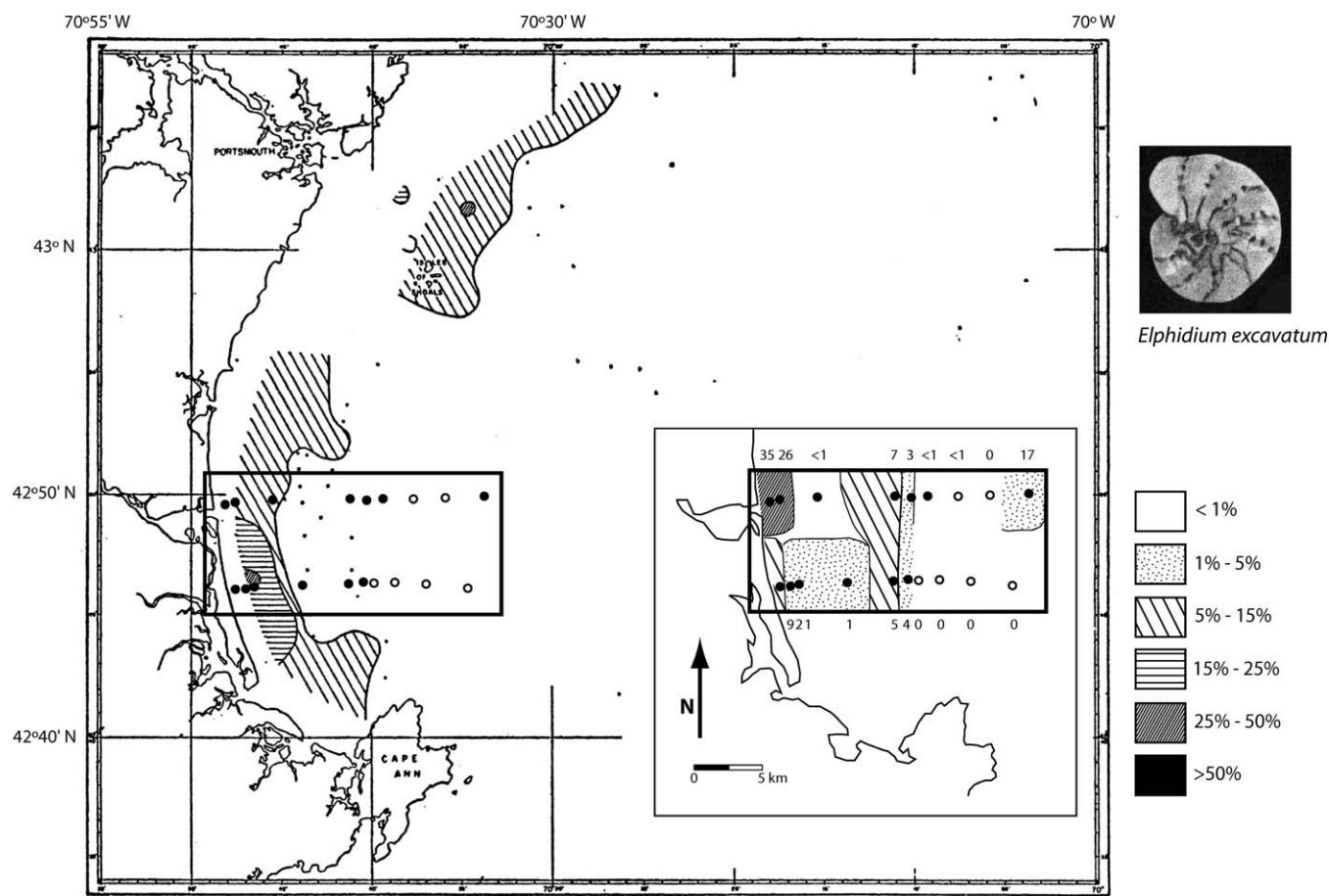


FIGURE 13. Distribution of *Elphidium excavatum* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

clustering process (Ryan et al., 2007). The analysis yielded several distinct foraminiferal assemblages: 1) a “shallow” assemblage, located at approximately 30-m water depth but where Transect 1 and Transect 2 samples cluster separately; 2) a “deep” assemblage at 40–100-m water depth, where, again, Transect 1 and Transect 2 samples cluster separately; and 3) a “delta edge” assemblage at approximately 50-m water depth (Fig. 8).

FORAMINIFERAL DISTRIBUTIONS

This section discusses the three overarching findings of this study that: 1) foraminiferal assemblages change from proximal to distal across the delta; 2) they differ from one transect to another; and 3) they can be used to verify geophysical and sedimentological data used to assess offshore sand and gravel resources. Figure 6 summarizes these three findings by depicting 10 of the most common benthic foraminiferal species described below. Additional species were not included in Figure 6 to reduce overcrowding the pie diagrams.

Proximal to Distal Changes in Foraminiferal Assemblages

Benthic foraminifera were more abundant (i.e., number of fossils/gram of sand-sized residuals) with increasing water depth along both transects, a distribution pattern

seen along other coastal margins (e.g., Gibson & Buzas, 1973; Leckie & Olsen, 2003). Phleger (1952) and Parker (1952) also observed increasing foraminiferal abundance with increasing depth, particularly in the southwest section of the Merrimack River Embayment. In contrast to the benthic species, planktic foraminifera were very rare in this study, being observed in isolated samples and often as single occurrences. The abundances of the 62 species identified in this study are presented in Appendix 2. The relative abundances and distributions of 27 of these 62 species (which account for 91% of all tests) are described in Appendix 1.

The species identified in this study tend to fall into three geographic distributions or biofacies: 1) species that primarily inhabit the delta plain (<50 m); 2) species that primarily inhabit the delta front (~>60 m); and 3) species that inhabit the delta break and overlap with the delta plain/delta front taxa. Each of these three biofacies has a distinctive species assemblage that overlaps with an adjacent biofacies. This allows each assemblage to delineate a specific area of the delta and serve as a proxy for sediment composition (Table 2). Phleger (1952) and Parker (1952) considered there to be two principal biogeographic provinces for the western Gulf of Maine, a sand facies and a mud-sand/mud facies. They also recognized that there may be one or more distinct subfacies and that overlap was likely.

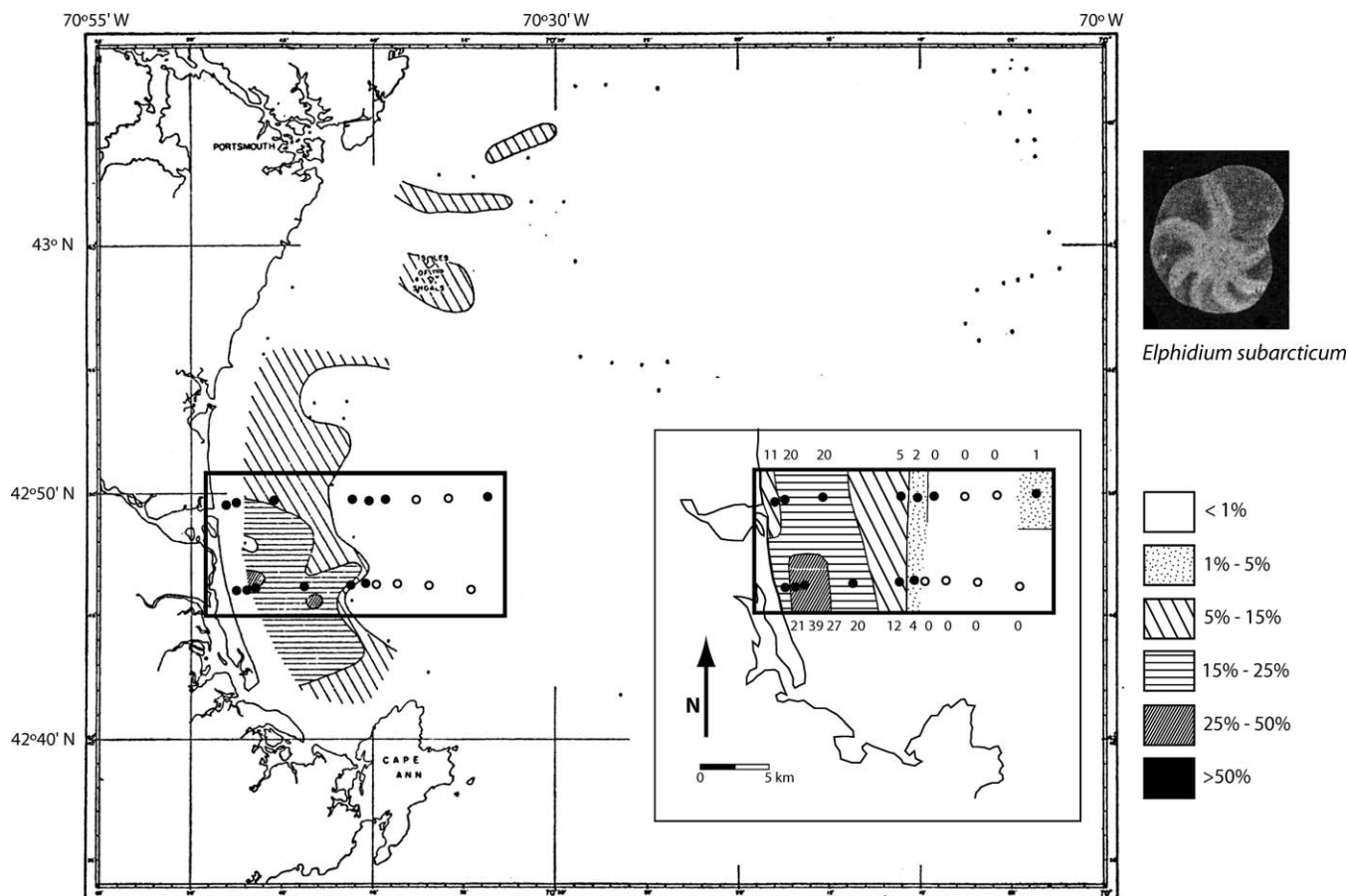


FIGURE 14. Distribution of *Elphidium subarcticum* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

The distribution and relative abundances of 14 benthic foraminiferal species are presented as biofacies maps (Figs. 9–22) that are discussed in the following sections. These species (Fig. 23) were selected for comparison purposes with as many biofacies maps produced by Phleger (1952) and Parker (1952) as possible. Five of their mapped species were not mapped here due to their rarity or absence from our study area and conversely we did not map some of our commonly occurring species that were unreported by Phleger and Parker.

Cibicides lobatulus (Walker & Jacob) is a calcareous species that exclusively inhabits the shallowest areas of the delta (Figs. 6 and 10), and thus, was unaffected by dissolution. It is much more common along Transect 1, having abundances of 32% at Site T1-1 and 24% at Site T1-2. Along Transect 2, *C. lobatulus* abundances peak at Site T2-20 (8%), but is absent at depths >60 m. At sites geographically comparable to this study, Phleger (1952) and Parker (1952) found *C. lobatulus* to have equal distributions along both transects, with peak abundances at ~20 m, yet absent below 50 m. Over a larger geographic area, Phleger (1952) and Parker (1952) observed *C. lobatulus* as having peak abundance near shore north of the Merrimack River. In comparison, we found that *C. lobatulus* has retreated landward, becoming much more constrained along the

shore and much more abundant near the mouth of the Merrimack River.

Globobulimina auriculata is a large calcareous species that inhabits the delta front (Fig. 6). It is most abundant at the deepest site (16.4%, 103.0 m, Site T1-10) and least abundant at Site T1-6 (2%, 59.0 m). Its absence in samples T1-8 (82.4 m) and T1-9 (92.3 m) is a likely indicator of dissolution since both samples were acidic after thawing. Although Phleger (1952) and Parker (1952) did not observe *G. auriculata* at sites comparable to this study, they did record this taxon at other locations in the region where water depths were >40 m.

The depth distribution of *Textularia torquata* Phleger & Parker extends from the delta break at 50.6 m to the delta front. Along Transect 1, *T. torquata* (an arenaceous species unaffected by dissolution) is most abundant at the delta front (24%, 71.5 m, Site T1-7; Figs. 6 and 21). The distribution and abundances of *T. torquata* observed in this study are similar to those of Phleger (1952) and Parker (1952). They found *T. torquata* to be more common in the muddy delta front, absent on the delta plain, and in greater abundances along Transect 1.

Adercotryma glomeratum (Brady) is an arenaceous species that becomes progressively more abundant along Transect 1 from the delta break (2% at 50.6 m, Site T1-5

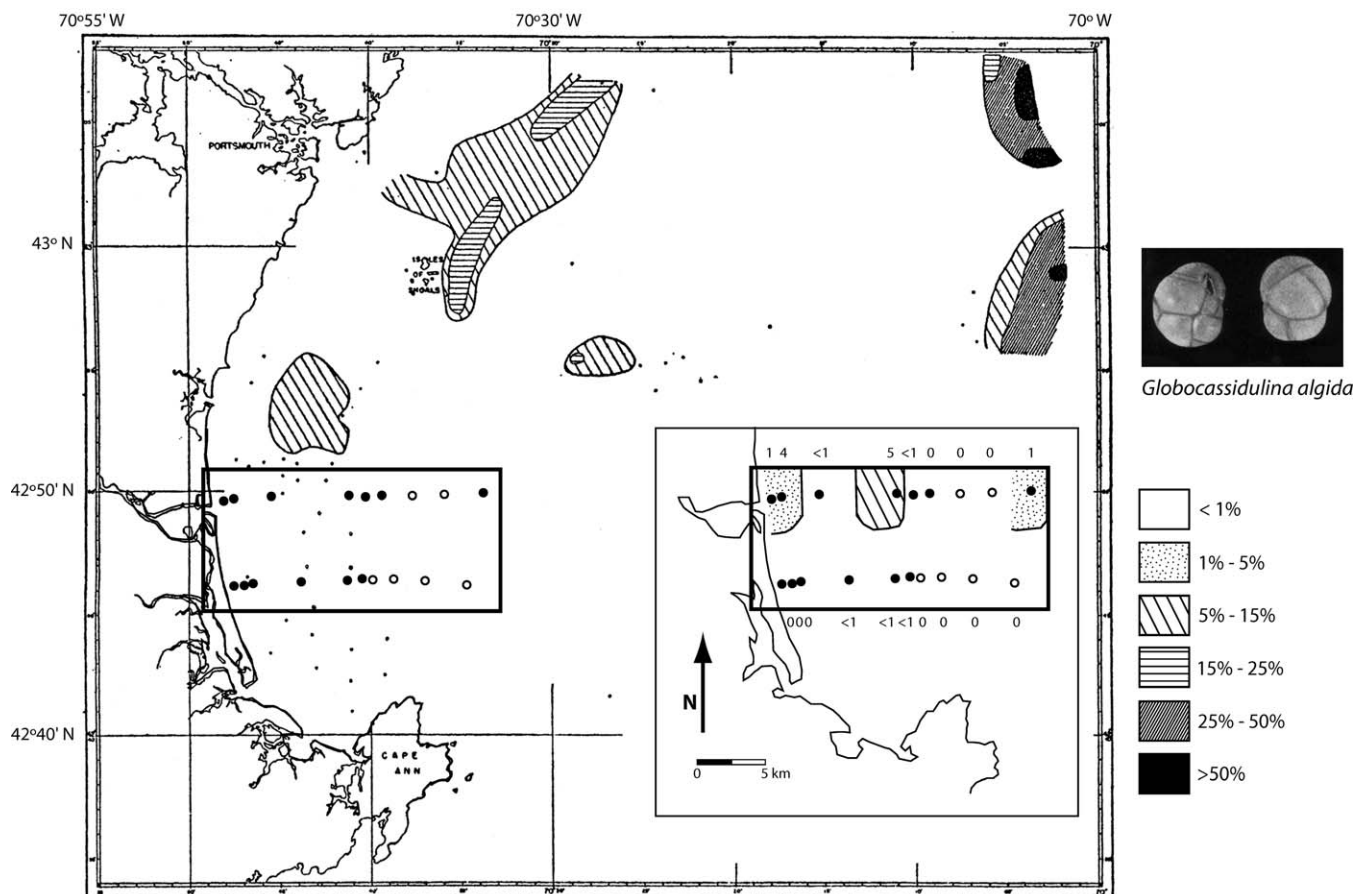


FIGURE 15. Distribution of *Globocassidulina alghida* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

and 16.9% at 71.5 m, Site T1-7) to the delta front (20% at 103 m, Site T1-10; Figs. 6 and 9). Transect 1 offers the clearest support for this trend because it had fewer acidic samples (T1-8 and T1-9) that dissolved calcareous specimens, skewing the assemblage counts. For Transect 2, the trend of increasing *A. glomeratum* abundance with increasing water depth is tenuous, but still supported. For example, it is unlikely that the observed abundance of *A. glomeratum* in the acidic sample T2-11 (52.4% at 92.5 m) would be lower than the abundance observed in the alkaline sample T2-15 (1.3% at 50.6 m) had dissolution not been an issue. Further, the alkaline sample T1-10 (103 m) serves as a guide as to how abundant *A. glomeratum* might have been if the deeper Transect 2 samples had not been affected by dissolution. At comparable locations to this study, Phleger (1952) and Parker (1952) reported *A. glomeratum* to be present in the muddy delta front and absent at the delta break and the delta plain, all the while having greater abundances along Transect 1. When considering the larger region covered by Phleger (1952) and Parker (1952), we observed that *A. glomeratum* has now shifted significantly closer to the shore and it is more abundant. The species' distribution along Transect 2 was indeterminate (Fig. 9).

Globobulimina auriculata and *C. lobatulus* are two calcareous species that have separate biogeographic biofacies. When combined with the arenaceous species *A.*

glomeratum and *T. torquata*, the four taxa delineate two broad biogeographic biofacies. The area covered by *A. glomeratum*, *G. auriculata*, and *T. torquata* ranges from the fine sands of the delta break to the muds of the delta front. *Cibicides lobatulus* is observed on the delta plain in fine to medium sands. The biofacies for these four species coincide with different seafloor sediments and demonstrate how the assemblages occupy different areas of the delta. This information in turn serves to confirm geophysical data that differentiate deltaic provinces.

The distributions and abundances of five additional species deserve mention. 1) *Spiroplectammia biformis* (Parker and Jones), is a species that Phleger (1952) and Parker (1952) found exclusively in the muddy delta front (Fig. 20). 2) *Cribrostomoides crassimargo* (Norman), which the latter workers also found to inhabit the more distal sections of the delta (Fig. 11), are largely unchanged in distribution and abundance over the past 60 years. 3) Both this study and Phleger (1952) and Parker (1952) found *E. subarcticum* to range from the delta plain to the delta break, with roughly the same abundances (Figs. 6 and 14). 4) Over comparable study areas, *Eggerella advena* (Cushman) today is considerably less abundant across the delta plain and front than observed by Phleger and Parker in 1952 (14% then vs. 39% this study; Table 1). In Long Island Sound, Thomas et al. (2000) also found a strong decrease in *Eg.*

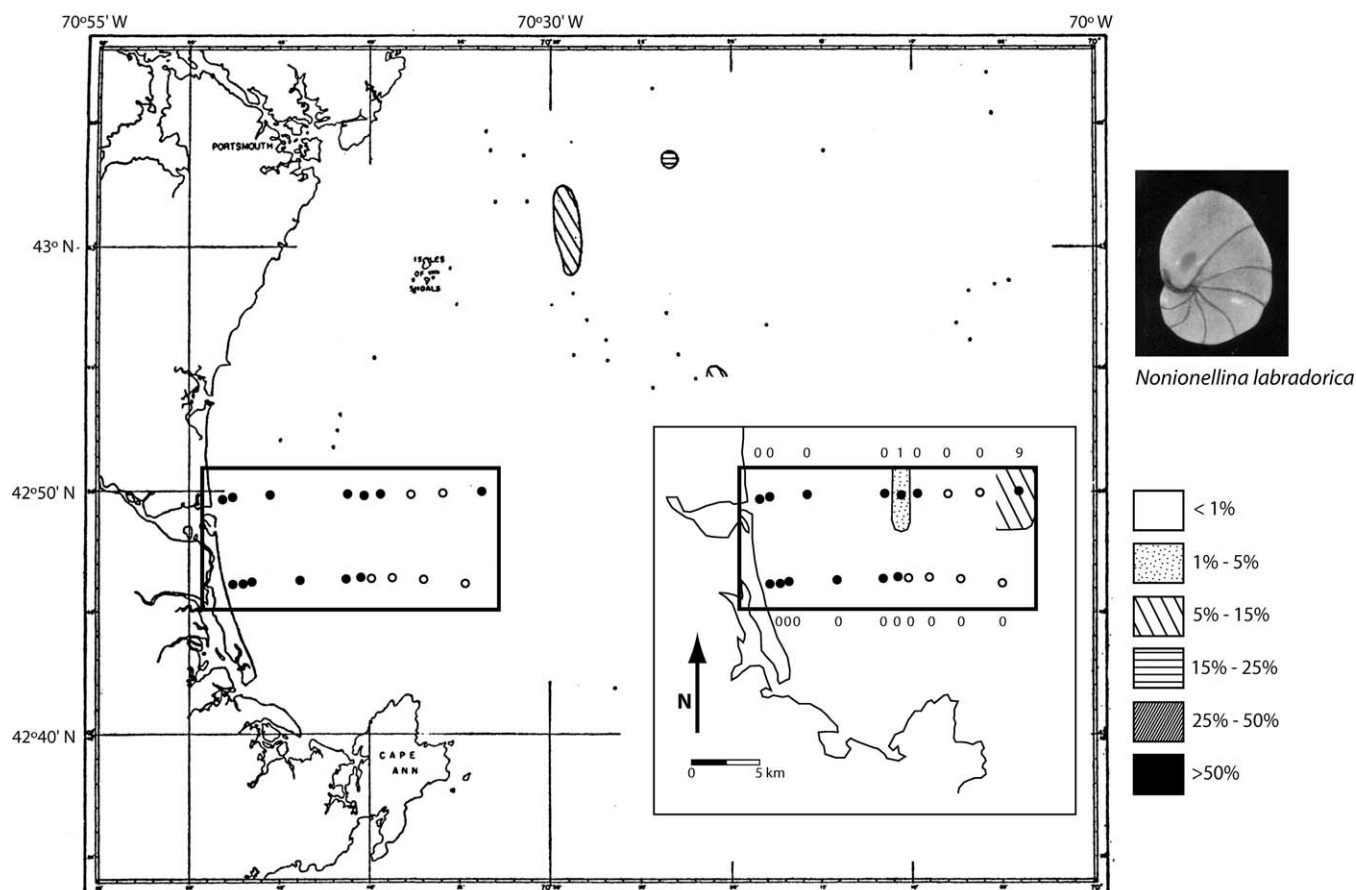


FIGURE 16. Distribution of *Nonionellina labradorica* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

advena abundances since the 1960s (Buzas, 1965) and speculated that the decrease may have been influenced by changes in food supply, specifically, there being proportionally more “fresh phytoplankton” associated with increased eutrophication of Long Island Sound and less degraded and refractory organic matter. 5) *Reophax curtus* Cushman (Fig. 17) is observed in our study along a broad north–south band that is centered near the delta break. It is absent near the shoreline, and rarely occurs in deep water. This distribution is a significant departure from Phleger (1952) and Parker (1952), who observed the species becoming more abundant with increasing depth and distance from the delta break (Fig. 17).

What controls the observed proximal to distal changes in foraminiferal distributions across the Merrimack Embayment is not entirely resolved. We argue that, collectively, foraminiferal distributions are independent of sediment type, per se, although some species distributions appear to follow sediment type more closely than others (Figs. 9–22). The data presented here suggest that foraminiferal distributions are primarily controlled by food availability and/or the combination of other environmental variables. This conclusion is based on comparing our 14 biofacies maps with those of Phleger (1952) and Parker (1952; Figs. 9–22). Our maps do not reveal any obvious correlation between foraminiferal distributions and the bedforms observed by Hein et al. (2007; Fig. 3).

This implies that the processes controlling the formation and distribution of the bedforms, and the character of the seafloor sediments, are largely independent of the environmental variables that control benthic foraminiferal distributions. Specifically, the action of factors such as Merrimack River outflow, storm waves, tides, and bottom currents reshaping the seafloor and controlling sediment type at any one locality (e.g., Hein et al., 2007) may play less of a role in determining where benthic foraminifera live than other factors such as food availability, temperature, and salinity (e.g., Akpati, 1975; Jorissen, 1999; Sen Gupta, 1999; Leckie & Olsen, 2003). Phleger (1952) and Parker (1952) came to the same conclusion by stating that foraminiferal distributions in the western Gulf of Maine are largely independent of sediment type. In Long Island Sound, Buzas (1965) suggested that the proximal to distal distribution of benthic foraminifera (i.e., their depth zonation) is related to the distribution of their food supply. If this reasoning can be applied to the Merrimack Embayment, then the observed depth zonation of some benthic foraminiferal species may be controlled primarily by the distribution of their food. The quality or quantity of this food may have changed over the past 60 years, similar to Long Island Sound (Thomas et al., 2000), which may explain some of the observed changes in the distribution of benthic foraminifera since the studies of Phleger (1952) and Parker (1952).

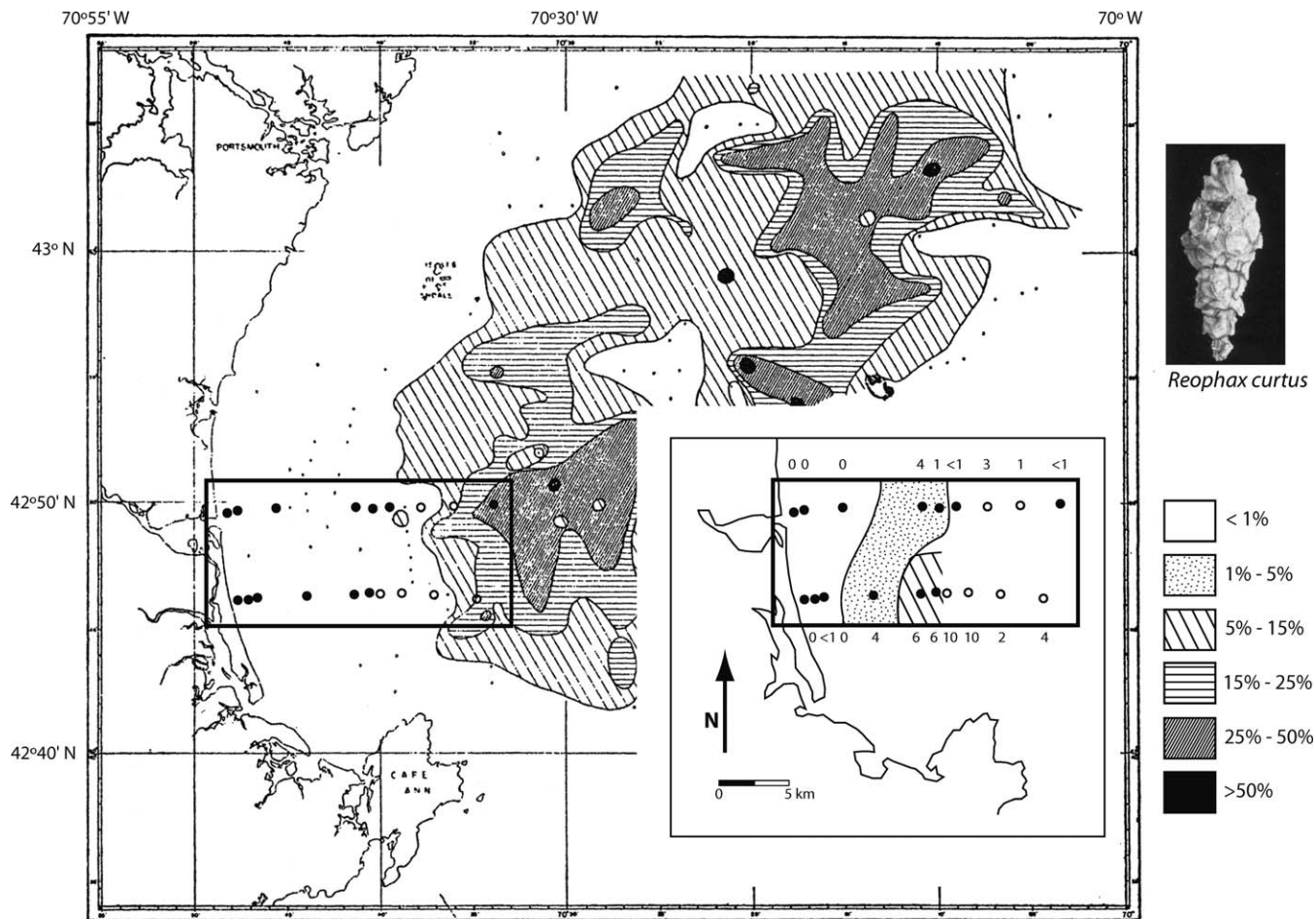


FIGURE 17. Distribution of *Reophax curtus* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

Transect 1/Transect 2 Foraminiferal Assemblages

Five species highlight differences in the benthic foraminiferal assemblages between the northern and southern transects in this study. For several species, the latitudinal differences between the two transects are accentuated when they are compared to the findings of Phleger (1952) and Parker (1952). These differences illustrate that the assemblages are not simply a function of increasing water depth parallel to the shore, nor are they a consequence of the delta's sedimentary composition changing distally. However, the transect differences are independent of dissolution effects.

Reophax scottii Chaster is an arenaceous species that was observed only along Transect 2 (Figs. 6 and 18). It inhabits the deltaic sands from 10–71.9 m, where the mud content reaches 52%. Peak abundance of *R. scottii* (27%) occurs at 50.6 m, coincident with the delta break. Its occurrence along only one transect so close to the shore is a significant departure from the biogeographic distribution observed by Phleger (1952) and Parker (1952). At sites comparable to this study and over a wider region, they observed *R. scottii* along a broad north–south band that followed the coastline and centered on the most proximal sections of the delta

front. They also reported *R. scottii* in very high abundances across limited areas (49% at 73 m) and to be very scarce or absent across the broad delta plain.

The distribution of *Trochammina squamata* Parker & Jones is similar to *R. scottii* in that this arenaceous species is found only along Transect 2 (Figs. 6 and 22). However, its abundance peaks at 19.8 m (11%) on the sandy delta plain and tapers off distally. Over the larger region, Phleger (1952) and Parker (1952) observed *Tr. squamata* along a narrow, north–south band parallel to the shoreline, coincident to that observed for *R. scottii*, although *Tr. squamata* did not reach as far north. In their study, *Tr. squamata* had peak abundances that were comparable to this study (~5–15%), but occurring in much deeper water (~80 m). Therefore, they regarded *Tr. squamata* to be characteristic of mud-sand sediments.

Saccammina atlantica (Cushman) is an arenaceous species whose most recent distributions and abundances depart significantly from those observed by Phleger (1952) and Parker (1952; Fig. 19). At sites comparable to this study, they found *S. atlantica* to be confined to a narrow, north–south band located on the sandy delta plain and break. Across the larger region, their abundances were relatively uniform. In this study, *S. atlantica* was found only in trace

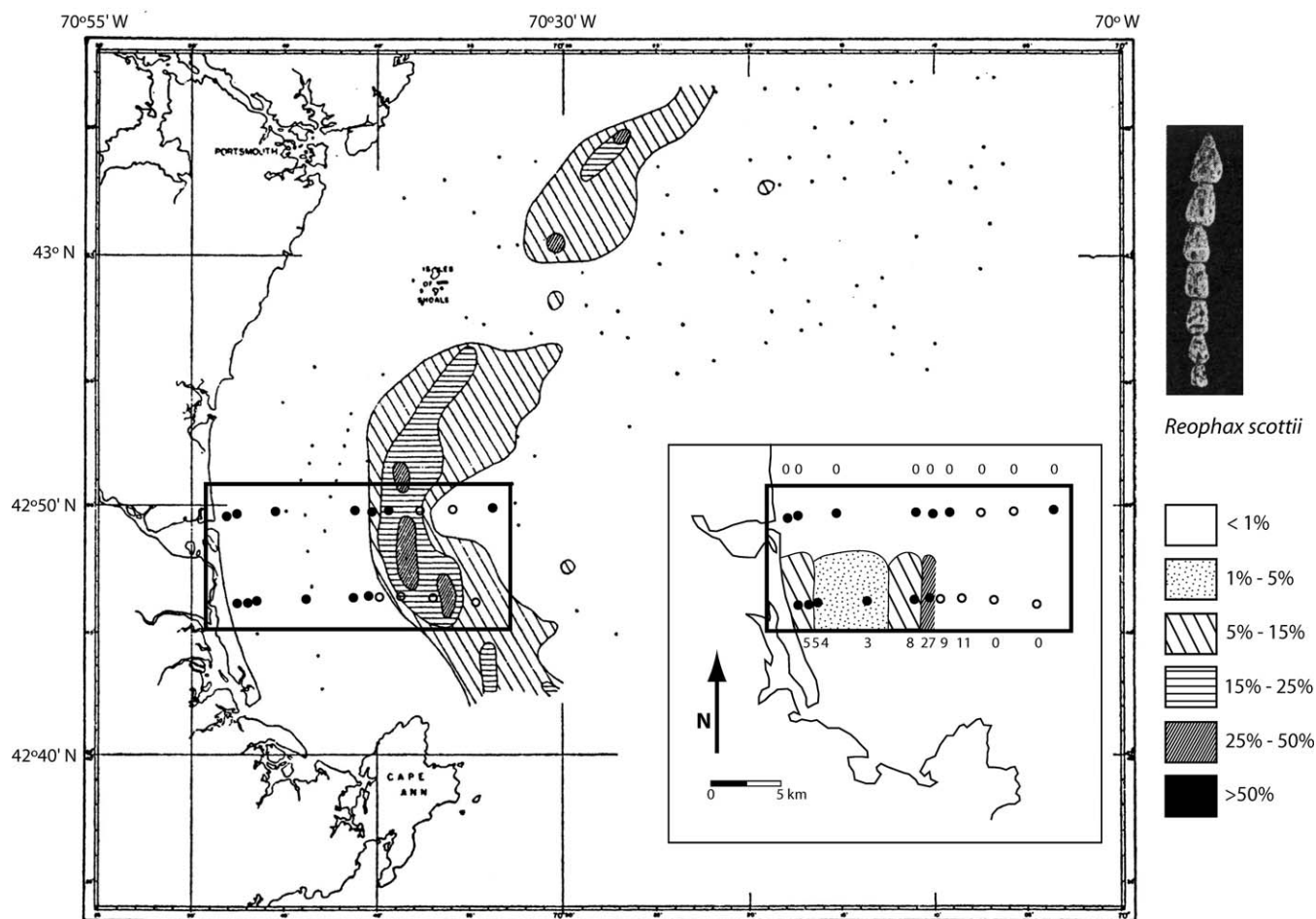


FIGURE 18. Distribution of *Reophax scottii* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

levels along Transect 1. Along Transect 2, it occurs in the fine to medium sands of the delta plain, but at water depths (30.2–50.6 m) that were similar to those in Phleger (1952) and Parker (1952). Our abundances of *S. atlantica* peak between 26–30% as compared to 11–18% in their studies.

The distribution and abundances of *Saccammina difflugiformis* (Brady) (an arenaceous species) follows *S. atlantica* (Fig. 6). The former species is found almost exclusively along Transect 2 (only two tests were obtained from Transect 1), and it was the 13th most common species in this study, with peak abundances ranging from 10% (62.6 m)–12% (30.2 m). Parker (1952) found *S. difflugiformis* to be uncommon across the Merrimack Embayment, but stated nothing more about its distribution and abundance. Phleger (1952) combined the species concept of *S. difflugiformis* with *S. atlantica* for tabulation purposes. Therefore, we could not make a rigorous comparison of our species data with theirs, although Phleger's combined occurrences indicate that his distribution of *S. difflugiformis* must have differed from ours.

Elphidium excavatum is a calcareous species found in all samples that were not affected by dissolution (Figs. 6 and 13). The species is most common in the shallowest areas of the delta plain along Transect 1 (35% at 9 m), with

abundances decreasing distally to the shelf break. The species is much less abundant along Transect 2, with a peak abundance of 9% at 10 m. The alkaline sample T1-10 at 103 m had *E. excavatum* abundances of 17%, an anomalous result that may be tied to sediment transport. Alternatively, it may be responding to a seasonal flux of organic matter to the seafloor, and thus, its occurrence at this deep site may be a short-lived spike in abundance. Phleger (1952) and Parker (1952) found abundant *E. excavatum* to be more constrained to the shoreline and more common along Transect 2 (peak abundance of 48%). They did not observe *E. excavatum* in water depths exceeding 41 m.

Thomas et al. (2000) found *E. excavatum* (therein referred to as *E. excavatum clavatum*) to be the most common foraminifera in Long Island Sound. As was occasionally observed within this study, Thomas et al. (2000) noted that this species sequesters chloroplasts that might actively photosynthesize within the foraminifera. If such is the case for the Merrimack Embayment, it may provide information about the depth of the photic zone in relation to the distribution of *E. excavatum*.

Two benthic foraminiferal species exemplify taxa that are rare and/or are found outside the area covered by this study. *Nonionellina labradorica* is absent in all delta plain

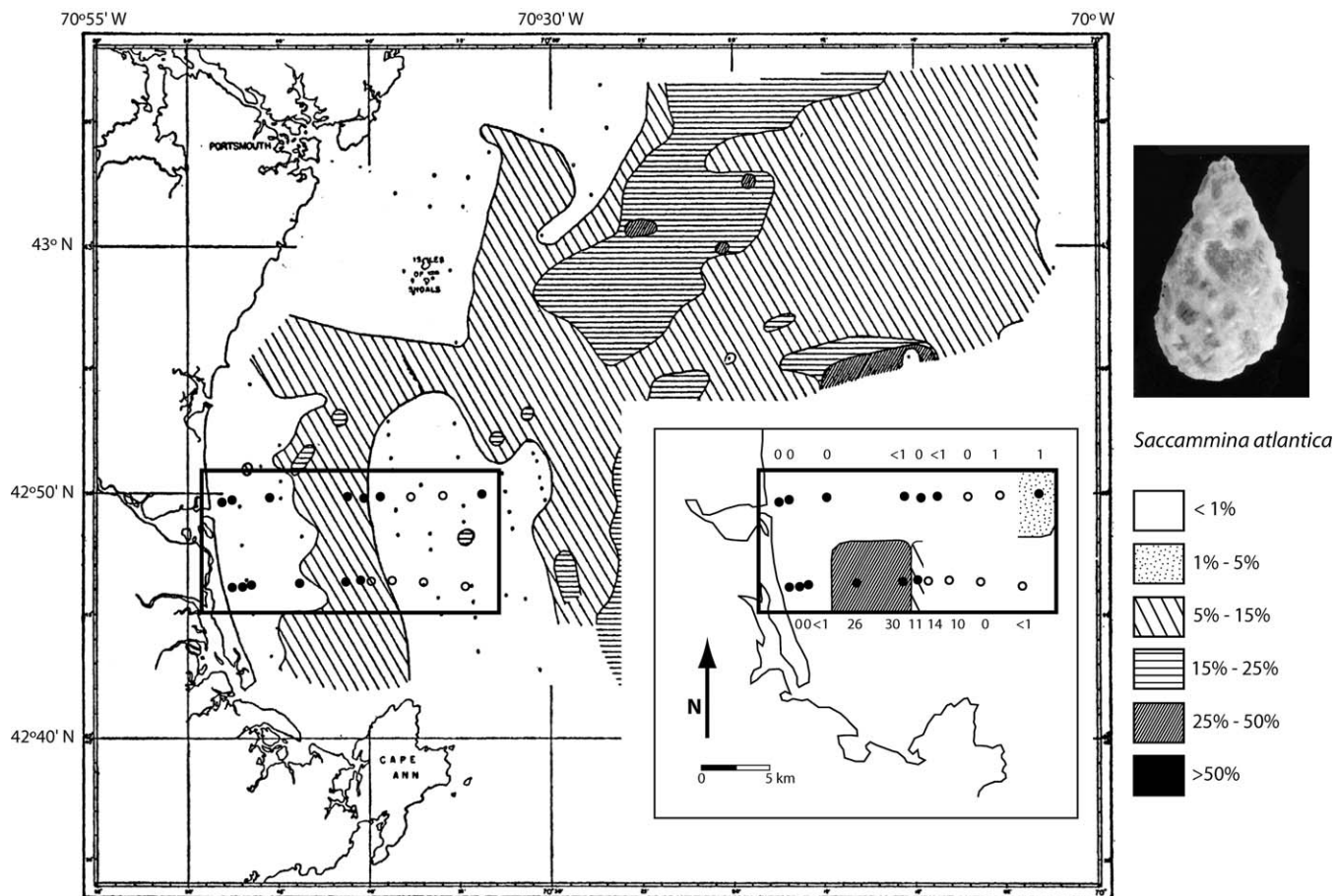


FIGURE 19. Distribution of *Saccammina atlantica* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

samples and all acidic samples. However, at Site T1-10 (103 m, an alkaline sample) *N. labradorica* has an abundance of 9% (Fig. 16). This finding is in keeping with Phleger (1952) and Parker (1952), who reported the species in moderate abundance but in very small, isolated patches across the western Gulf of Maine. *Globocassidulina algida* occurs in low percentages across Transect 1, has single occurrences along Transect 2, and is absent from all acidic samples (Fig. 15). This spotty distribution is similar to the pattern observed by Phleger (1952) and Parker (1952).

Why the distribution and abundances of *R. scottii*, *Tr. squamata*, *S. atlantica*, *S. difflugiformis*, *E. excavatum*, and *C. lobatulus* have changed so much from one transect to another over a 60-year period is open to speculation. Although sediment composition can vary significantly over distances as short as tens of meters within the Merrimack Embayment (Hein et al., 2007), it is a reasonable approximation that sediment composition changes parallel to the shoreline as water depth increases along both transects. Thus, the differences observed between the two transects in the distribution and abundance of a particular foraminiferal species, when compared to Phleger (1952) and Parker (1952), may be due to variables other than water depth and sediment composition. One possible cause may be changes in the water column brought about by the Merrimack River outflow.

The regional barrier islands demonstrate that local currents (i.e., longshore transport) follow the coastline, moving in a north-south direction (e.g., Fitzgerald et al., 1994; Hein et al., 2007, 2012). Transect 1 is positioned just north of a line running due east from the mouth of the Merrimack River, while Transect 2 is five kilometers to the south. Based on the position of the two transects and local oceanographic conditions, it seems reasonable to assume that Transect 2 is to some degree influenced more by the outflow of the Merrimack River than Transect 1 (Parker, 1952; Phleger, 1952).

The river outflow would affect all aspects of the water column, in particular its chemical and physical properties. One notable effect is the delivery and southward transport of nutrients from the river. These nutrients can influence biological productivity in the water column and on the seafloor, especially the abundance and distribution of macro- and microfaunal communities, of which benthic foraminifera are a part (e.g., Sen Gupta, 1999; Leckie & Olsen, 2003). The degree of biological productivity at a particular location also influences the quantity and quality of organic matter in the sediments. Thus, sandy environments that are in areas of higher productivity are likely to be richer in organics and contain different foraminiferal assemblages than sands in areas of lower productivity.

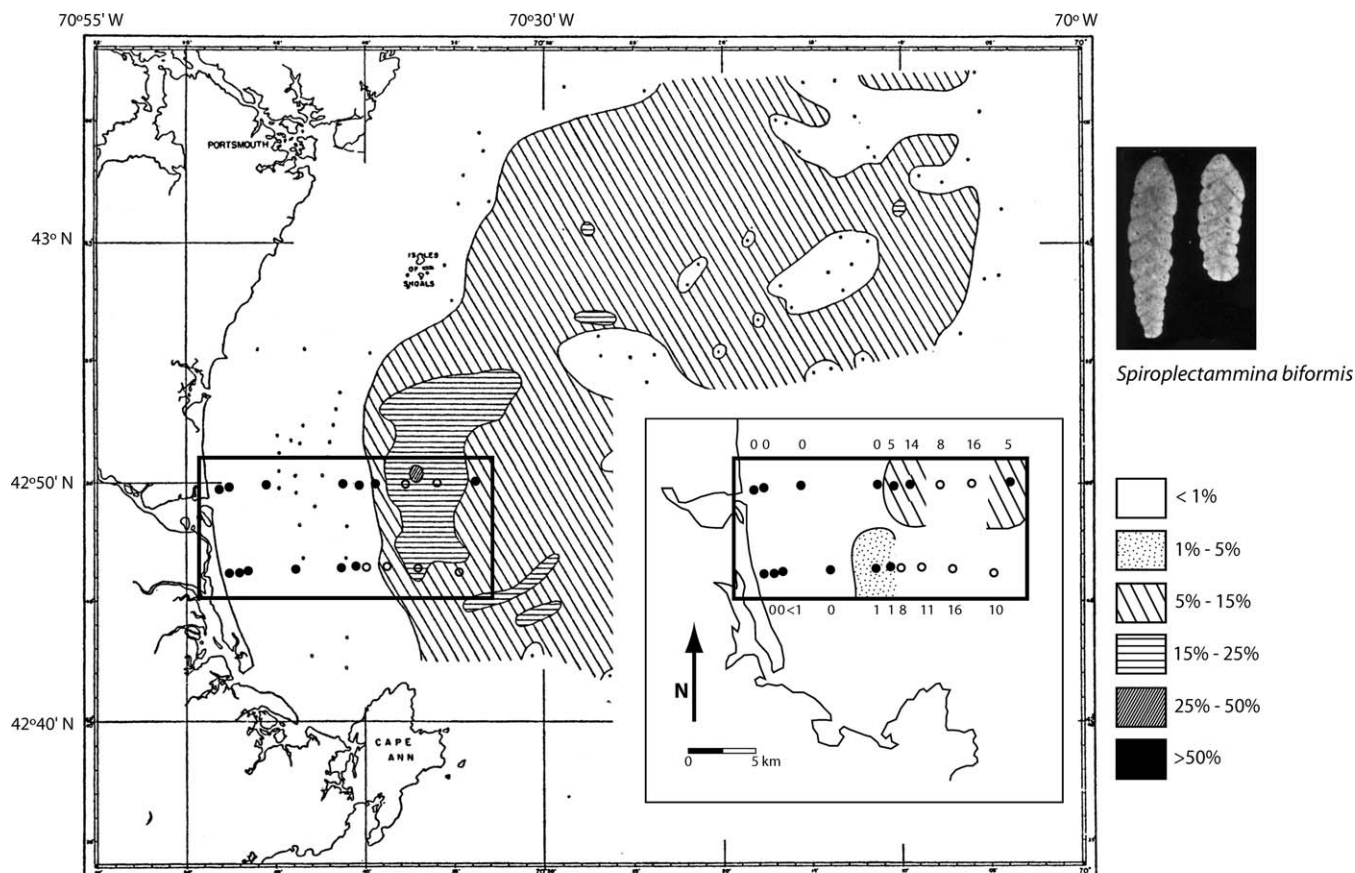


FIGURE 20. Distribution of *Spiroplectammina biformis* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

These variations may be one possible explanation for the biotic differences observed between Transect 1 and Transect 2, both today and six decades ago. Land-use changes in the Merrimack River watershed, affecting the composition of Merrimack River runoff, may have altered the nature of biological productivity offshore, and by extension, the nature of the benthic foraminiferal communities since the 1940s. For example, Thomas et al. (2000) documented a decrease in *Eg. advena*, a taxon that prefers more degraded refractory organic matter, in Long Island Sound with increasing eutrophication and higher biological productivity. Perhaps productivity changes have affected the benthic foraminiferal communities off the mouth of the Merrimack River and Plum Island, including a decline in *Eg. advena* and expanded distribution of *Elphidium* spp. across the Merrimack delta plain.

How far offshore the effects of the Merrimack River may reach is unknown. But, it is likely to be highly variable and dependent upon such factors as the season, meteorological events, currents, and how readily fluvial and marine waters mix.

Foraminifera and Geophysical/Sedimentological Techniques

Foraminiferal assemblages can serve to confirm geophysical and sedimentological techniques (or data). This theme has been supported by the data and interpretations

provided in this study. This section provides an overview of these findings.

The 14 biofacies maps (Figs. 9–22) delineate specific areas of the delta inhabited by individual species of benthic foraminifera. These maps also present the distributions of modern foraminifera in side-by-side comparison to the literature. The indirect association between foraminiferal distributions and sediment type allows these biofacies maps to complement maps that depict geophysical and sedimentological data. Figure 6 illustrates that each sampling site on the delta yields a unique assemblage of benthic foraminifera and associated grain size. Taken together with the side-scan-sonar and grain-size data (Fig. 4), it is clear that the changing foraminiferal assemblages can be used to delineate the delta plain, delta break, and delta front.

Cluster analysis of foraminiferal abundances provides a mathematically independent method to confirm or refute the interpretations of the biofacies maps and the observed assemblages. This analysis consistently shows sample sites grouping as “shallow” (~30 m), “deep” (~40–100 m), and “delta edge” (~50 m), in keeping with the broad morphological features of the delta plain, break, and front, respectively. In some cases, samples from both transects clustered together (Fig. 8), while in others cluster analysis grouped samples that experienced dissolution due to laboratory preservation. The latter grouping effect contributes to some of the disparity between the assemblage depths

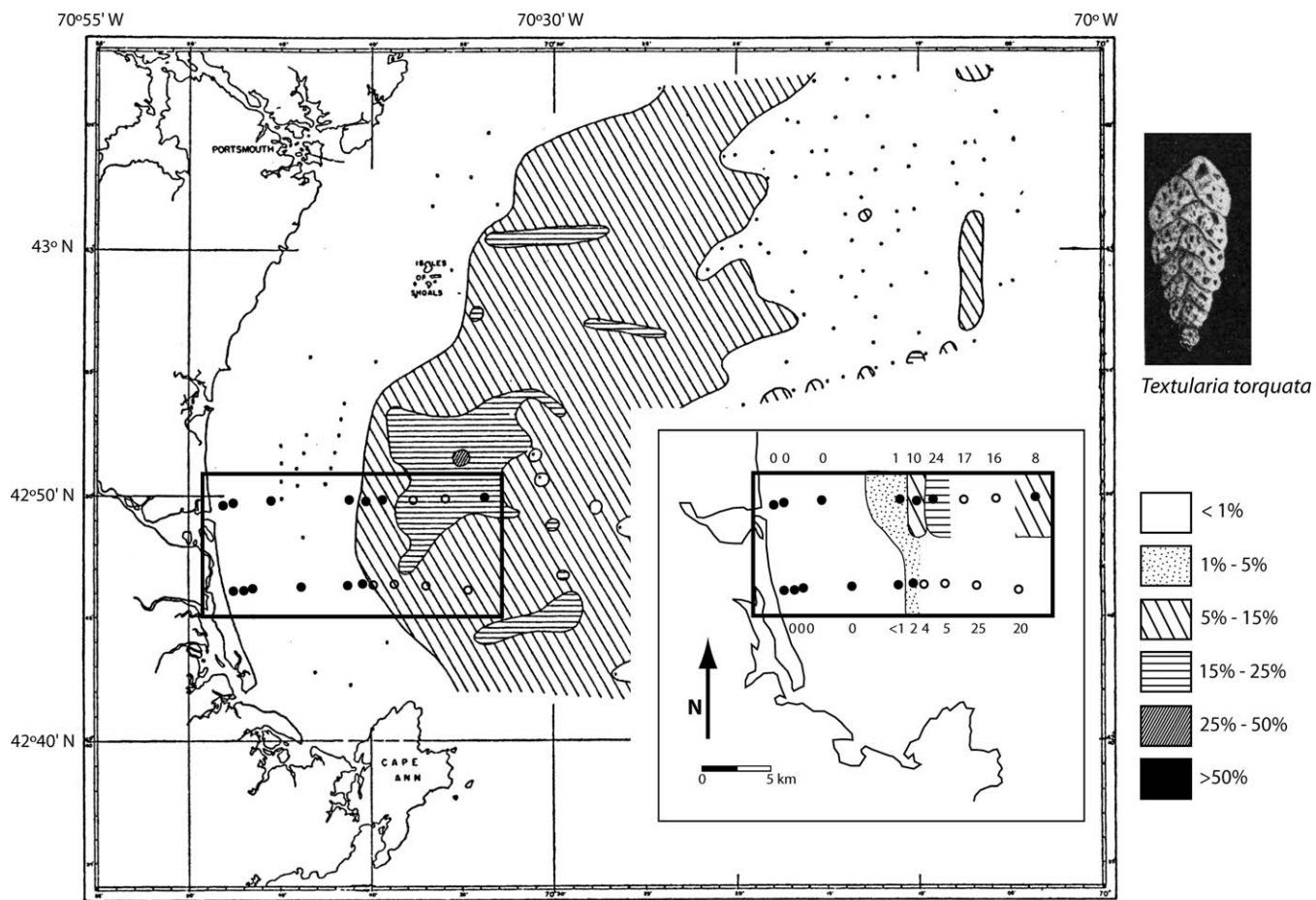


FIGURE 21. Distribution of *Textularia torquata* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

revealed by cluster analysis and those shown by other measures (e.g., species richness). The distinction between the shallow assemblages that occupy the delta plain and the deep assemblages of the delta front may be attributed to substrate characteristics. Fine to coarse sands characterize the seafloor in water depths shallower than 40 m, while mud becomes increasingly abundant at greater depths.

There is good agreement between the distinct groupings identified by cluster analysis and those revealed by measurements of species richness, evenness, and dominance. These analyses show at a minimum that foraminiferal assemblages do differentiate the sandy delta plain from the muddy delta front, as well as identify the delta break. The analyses of the foraminiferal assemblages also show significant differences between the two transects although sediment character and water depth for both transects change parallel to the shore and are similar to one another. This biotic information complements the findings of the geophysical and sedimentological techniques that are used for mapping the extent and character of each part of the delta.

In comparison to the Merrimack Embayment, Thomas et al. (2000) found that species richness in Long Island Sound has decreased since the 1960s. They suggested that environmental stress from seasonal hypoxia, pollution, or other variables have caused the changes in species' relative

abundance. However, seasonal hypoxia is not an issue in the open-shelf conditions of the Merrimack Embayment.

It is useful to remember that the assemblages and their characteristics as discussed here (i.e., richness, evenness, and dominance) represent an annual average of a seasonal progression of changing assemblages. Knowing how the assemblages change seasonally would provide an added dimension to understanding the benthic foraminiferal communities and the benthic environment.

Table 1 shows that the three most common species in Phleger (1952) and Parker (1952) account for 53% of all tests in a comparable area. For this study, the six most common species account for 51% of all tests. This implies a greater evenness and correspondingly less dominance among the assemblages today than during their research.

Benthic foraminifera are sensitive to environmental changes and a number of studies have examined foraminiferal responses to anthropogenic pollution, habitat disturbance, and global warming (e.g., Scott & Lipps, 1995; Yanko et al., 1999; Scott et al., 2003; Dabbous & Scott, 2012). By monitoring proxies such as test deformities and anomalous changes in species populations, benthic foraminifera could provide insight into changing depositional conditions in the Merrimack Embayment (e.g., Dabbous & Scott, 2012). In this study, test deformities were very rare. The benthic

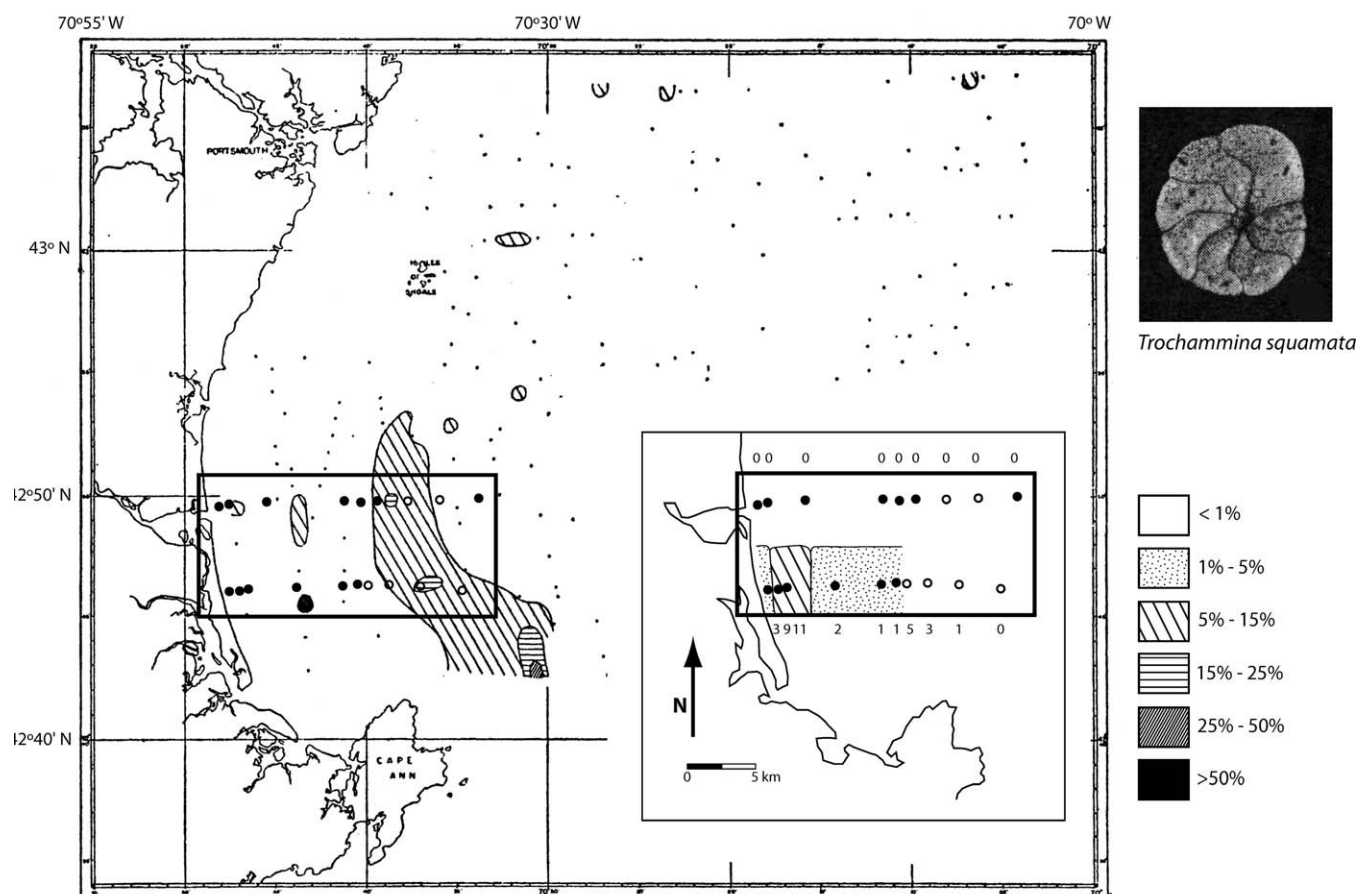


FIGURE 22. Distribution of *Trochammina squamata* in percent of total population of benthic foraminifera. See Figure 9 for explanation of large map and inset map.

species *Sp. biformis* exhibited the largest number of atypical tests, but the deformities in test shape were minor (e.g., tests having a 90° rotation along the long axis). Abnormal tests also occurred, although very rarely, in *C. lobatulus*, *Cr. crassimargo*, *E. subarcticum*, *S. difflugiformis*, *Sp. typica* Lacroix, and *Tr. lobata* Cushman. They were found along both transects and at most water depths, but were slightly more common near the delta break. Although limited in number, these observations of test deformities provide a valuable baseline for future work given the current scarcity of data for the Merrimack Embayment.

SUMMARY AND CONCLUSIONS

Benthic foraminiferal analyses were carried out on box core sediment samples collected in two depth transects perpendicular to the shore off the mouth of the Merrimack River (Transect 1) and off Plum Island (Transect 2) in the Merrimack Embayment north of Cape Ann. Our data were coupled with grain-size analyses and to a lesser degree geophysical techniques to delimit modern depositional environments. This study found:

- 1) Individual species tend to exhibit a general depth zonation by inhabiting distinct biogeographic areas of the paleo-delta. Fourteen biofacies maps depict and

compare recent biogeographic distributions of selected benthic species to their spatial distributions observed nearly 60 years earlier by Phleger (1952) and Parker (1952). Many of these species have exhibited a landward shift in their distributions (e.g., *Adercotryma glomeratum*, *Cibicides lobatulus*, *Reophax curtus*, and *Trochammina squamata*), while a few exhibited wider and more distal distributions (e.g., *Elphidium excavatum* and *E. subarcticum*). To what degree the observed changes in species distributions are due to changes in food supply (biological productivity, riverine input) or seafloor disruption due to large winter storms or fishing activity (bottom dragging) is not known.

- 2) Significant differences in the distribution of some benthic foraminiferal species exist between the two transects sampled in this study (e.g., *Reophax scottii*). These differences may point to the influence of circulation and seasonal productivity in the southwestern portion of the Merrimack Embayment, and/or the influence of the Merrimack River outflow upon the two transects. In particular, changes from land use in the Merrimack River watershed or in environmental impact from the Merrimack River runoff may have changed the nature of productivity over the past six decades. The two transects may experience different

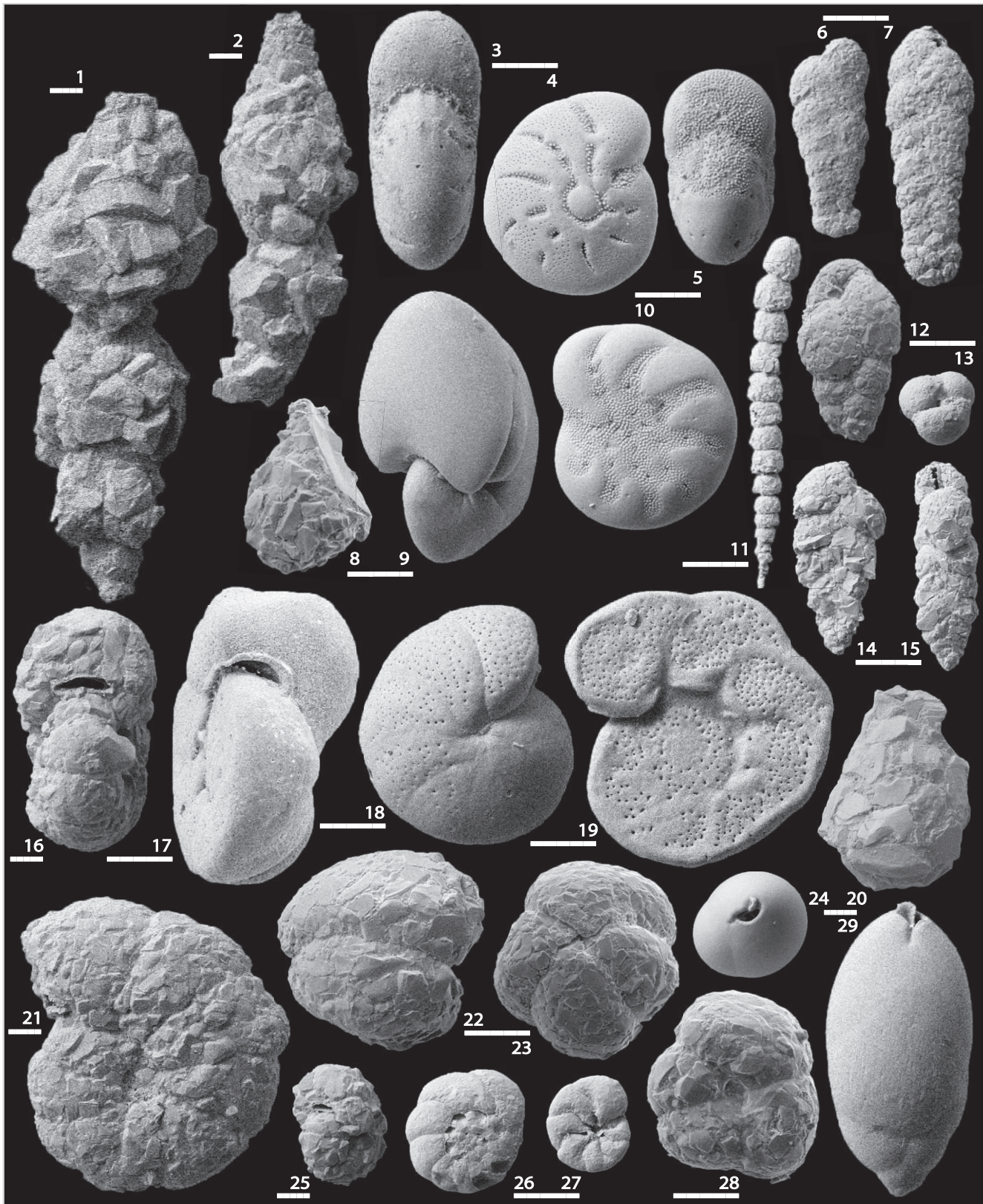


FIGURE 23. Key benthic foraminifera of the Merrimack River delta; scale bars = 100 μm . 1, 2 *Reophax curtus*; 3, 4 *Elphidium excavatum*; 5, 10 *Elphidium subarcticum*; 6, 7 *Spiroplectammina biformis*; 8 *Saccammina difflugiformis*; 9 *Nonionellina labradorica*; 11 *Reophax scottii*; 12, 13 *Eggerella advena*; 14, 15 *Textularia torquata*; 16, 21, 25 *Cribostromoides crassimargo*; 17–19 *Cibicides lobatulus*; 20 *Saccammina atlantica*; 22, 23, 28 *Adercotryma glomeratum*; 24, 29 *Globobulimina auriculata*; 26, 27 *Trochammina squamata*.

water-column conditions, which, in turn, affects the flux and nature of food availability at the seafloor. This may explain the striking asymmetry in foraminiferal assemblages observed between the northern and southern transects.

- 3) Unique assemblages of benthic foraminifera characterize each sampled area of the Merrimack River paleo-delta (see Fig. 6). These assemblages help delineate specific areas of the delta including the sandy delta plain, muddy delta front, and transitional delta break.
- 4) Benthic foraminiferal distributions are independent of local bedforms. Local foraminiferal distributions may be driven more by the distribution of food supply, which is associated with sediment type.
- 5) Foraminiferal species distributions and populations, as well as cluster analyses and indices of species richness, evenness, and dominance, all serve to delineate the paleo-delta in a manner that complements geophysical and sedimentological data. Independent of geophysical techniques, benthic foraminifera might also serve as a proxy for substrate conditions pre- and post-sediment disruption. For example, benthic foraminifera might be used to gauge biotic recovery from offshore mining of sand and gravel resources by analyzing recolonization trends and rates. This is a key determination to make with respect to assessing the impact of any planned activity and for environmental permitting;
- 6) This study did not demonstrate environmental changes based on the quantification of test deformities, due to the limited scope of the project. However, the collected data will serve as a useful baseline to the larger study that would be needed to assess pollution and changes in productivity and habitat disturbance.
- 7) This study demonstrates the need to reexamine the Merrimack Embayment and the western Gulf of Maine on the scale undertaken by Phleger (1952) and Parker (1952). Increasing regional anthropogenic pressures that range from watershed development, coastal environmental impact (e.g., rising sea level and pollution), and marine development (e.g., increased fishing activity and mining of subaqueous sand and gravel deposits) all demand a more comprehensive understanding of the region prior to the implementation of any effort to utilize these resources or to mitigate human impact.

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APPENDIX 1

Alphabetical list of the 62 species observed in this study. Although the species concepts of Cushman (1944), Parker (1952), and Todd & Low (1981) were closely followed, a short commentary of key species is provided, as well as a brief description of their abundances and distributions. For the benefit of the reader, a brief synonymy is given after the name of the species (where appropriate). Key benthic foraminifera of the Merrimack River delta are illustrated in Figure 23 of the published paper. This appendix can be found on the Cushman Foundation website in the JFR Article Data Repository (<http://www.cushmanfoundation.org/jfr/index.html>) as item number JFR_DR2014004.

APPENDIX 2

Benthic foraminiferal abundances. This table can be found on the Cushman Foundation website in the JFR Article Data Repository (<http://www.cushmanfoundation.org/jfr/index.html>) as item number JFR_DR2014004.